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MILITARY OPERATIONS RESEARCH SOCIETY

Military Operations Research

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Military Applications Society

Institute for Operations Research and the Management Sciences

The Military Applications Society (MAS) is a democratically constituted professional society of open membership dedicated to the free and open pursuit of the science, engineering and art of military operations. It is the first society of the Institute for Operations Research and the Management Sciences (INFORMS). MAS advances research in military operations, fosters higher standards of practice of military operations research, promotes the exchange of information among developers and users of military operations research; and encourages the study of military operations research.

The society sponsors two open meetings annually, publishes a book series "Topics in Operations Research," and, among other activities, jointly publishes *PHALANX* and *MILITARY OPERATIONS RESEARCH* with the Military Operations Research Society.

Executive Summaries

UNMANNED AERIAL VEHICLE (UAV) ROUTE SELECTION USING REACTIVE TABU SEARCH

by Joel L. Ryan, T. Glenn Bailey, James T. Moore, and William B. Carlton

In recent years the Air Force has begun employing unmanned systems, such as the Predator unmanned aerial vehicle (UAV), on surveillance and reconnaissance missions in the Balkans and Southwest Asia. The typical mission profile often involves fifty or more targets during a 24-hour period, where each individual target requires that overhead surveillance begin within a specified time of the day. Furthermore, the amount of reconnaissance time required for each target is unknown in advance, and surface-to-air threats can exist both enroute and at certain targets. Consequently, these conditions present a major challenge to UAV operators and mission planners when deciding how to sequence a mission's targets.

In this paper Joel Ryan, Glenn Bailey, Jim Moore and Bee Carlton present a reactive tabu search (RTS) heuristic within a Monte Carlo simulation to solve such routing problems for UAVs. Their formulation models this problem as a multiple traveling salesman problem with time windows, with the hierarchical objective of first maximizing expected target coverage, then minimizing total travel time. The authors demonstrate their technique on a notional Bosnia scenario using an object-oriented implementation of this approach.

AN HISTORICAL PERSPECTIVE ON OPERATIONS RESEARCH IN THE UNITED STATES AIR FORCE

by Carl M. Harris, and Frank T. Trippi

The following paper is an electronically scanned version of an in-office manuscript prepared by Dr. LeRoy A. Brothers in September 1952, at which time he was Chief of the Operations Analysis Division in the Office of the Air Force Deputy Chief of Staff for Operations. The paper provides a complete discussion of the origins, development, and successful application of operations analysis in the Air Force up to the middle of the Korean War. Roy Brothers' formal career in OR only spanned the brief period 1943–1958, taking him from the faculty at Drexel Institute first into operations analysis dealing with targets and weapons for the war in the Far East and the U.S. Strategic Bombing Survey operations in Japan, and then to civilian time as a coordinator of strategic, tactical and defense studies at Air Force Headquarters in Washington, D.C. Dr. Brothers returned to Drexel in Fall 1958 as Dean of the School of Science and Engineering. But, despite his relatively short career in OR, his contributions to OR were significant. Throughout his time with the Air Force, he showed outstanding insights regarding the role of quantitative methods in national defense decision making, and was an exemplary leader of the kinds of interdisciplinary teams of civilian and career staff so necessary for military problem solving. In 1955, LeRoy A. Brothers served as the fourth President of the Operations Research Society of America, and his term was marked by special foci on understanding the major ingredients of successful OR project work and the development of appropriate paradigms for OR education. We believe that Dr. Brothers' words are especially germane for today's community of practicing military operations research analysts.

MODELLING THE MOBILE LAND BATTLE: COMBAT DEGRADATION AND CRITERIA FOR DEFEAT

by L. R. Speight and D. Rowland

This article reviews some of the evidence concerning what is known about the degradation of combat skills in battle. It puts forward a scheme for the representation of this effect in battle models, and then links this to the odds of 'victory' or 'defeat' in mobile land warfare.

The historical evidence suggests that, in mortal combat, only a modest proportion of weapon crews can be relied on to make a fully active contribution to the battle. Of the remainder some will make only an intermittent contribution, and some no contribution at all. It appears that there are relatively stable differences in these proportions from one army to another. The evidence also suggests that the contribution of the less effective is likely to be somewhat more in the attack than in the defence. The article shows how this phenomenon could affect the form of mathematical models and predictions commonly used to represent combat attrition.

Historical analysis also suggests that, at the tactical level, successful resistance to attack depends less on attrition than it does on maintaining the spatial integrity of the

defence. Clearly, this integrity is more likely to be compromised as the proportion of non-contributing defenders increases. A simple modelling scheme is therefore proposed. That sector in which the attacker intends to break through is designated as the 'critical point'. If, when the attacker reaches this 'critical point', the number of his survivors equals or exceeds a pre-determined multiple of the **active** surviving defenders in this sector, then the attack will be deemed to have 'succeeded'. Although simplistic, and obviously in need of refinement, this scheme does provide a plausible explanation for some observed operational relationships: that armies which characteristically impose low casualty rates on their attackers tend to surrender when their own casualty rates are low, and also tend to retreat at a faster rate as a function of local force ratio.

ENVIRONMENTAL FACTORS IN AMPHIBIOUS OPERATIONS

by Donald R. Del Balzo, A. Vodola and Jerry D. Beveridge

This article provides an overview of an effort to quantify the impact of environmental factors on amphibious operations. Two primary objectives of the analysis are summarized:

- Develop a methodology to rank-order environmental factors in proportion to their impact on warfare effectiveness.
- Demonstrate the operational impact of the environment using methods and measures employed in high-level studies as part of the Navy assessment and budgeting process.

A decision-theoretical methodology was developed to rank-order a complete spectrum of 36 environmental factors. The study determined that factors such as visibility and terrain that impact fundamental capabilities such as sensing, mobility, and targeting, would top the list in most scenarios. The ranking of individual factors with those and other broad categories is sensitive to scenario, season, and to the anticipated concept of force employment.

The operational analysis demonstrated how adverse conditions could defeat a mission plan and used a high-level measure of effectiveness to indicate the resulting impact on mission success.

The rank-ordering methodology provides a big-picture operational perspective to researchers in environmental science, modeling, and data collection. The high-level impact analysis puts environmental research and products on the same footing as traditional research, development, and procurement of combat systems from the perspective of program planners and decision-makers. Such analysis highlights the extent to which operational assessment analysis depends on the environmental context and allows environmental programs and products to be traded off against sensors, weapons, and platforms.

These methodologies could be adapted to assess environmental impacts on additional naval warfare missions and even, joint warfare operations.

DEPOT-LEVEL MAINTENANCE PLANNING FOR MARINE CORPS GROUND EQUIPMENT

by Christopher A. Goodhart

Life cycle management of military equipment represents the integration of force structure decisions, current and future operational needs for equipment, modernization, fielding and retirement plans, and supply and maintenance support. The Marine Corps traditionally has regarded each of these activities separately from the others, and has treated them independently in planning and programming. In an increasingly resource competitive environment, integrated life cycle management must become more clearly evident in the planning and programming processes that ultimately provide resources for these activities. This paper presents a mixed-integer linear program used by the Marine Corps to develop two- to six-year depot-level maintenance plans for its ground equipment in consonance with other life cycle management activities. The model presented explicitly considers established fielding, modernization and retirement plans while maximizing the aggregate value of available equipment each year, ensuring that an adequate number of each asset type is available when needed and that annual budget limits are observed. Results obtained for fiscal years 2000–2005 helped achieve a 40% increase ($30M) to depot-level maintenance funding for fiscal year 2000 and dramatically reduced the plans' preparation time while producing a balanced mix of equipment to address operational needs.

Unmanned Aerial Vehicle (UAV) Route Selection Using Reactive Tabu Search

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OR METHODOLOGIES:
Multiobjective Optimization, Simulation
APPLICATION AREA:
Unmanned Systems

ABSTRACT

We apply a reactive tabu search (RTS) heuristic within a Monte Carlo simulation to solve routing problems for unmanned aerial vehicles (UAVs). Our formulation models this problem as a multiple traveling salesman problem with time windows, with the hierarchical objective of first maximizing expected target coverage, then minimizing total travel time. The RTS heuristic incorporates weather and probability of UAV survival at each target as random inputs in the simulation's search for the best solution of each realization of the problem scenario in order to identify those routes that are robust to variations in winds, threat, or target service times. This technique is then extended to quantify the marginal contribution of additional UAVs to mission accomplishment. We present an object-oriented implementation of this approach using CACI's simulation language MODSIM.

INTRODUCTION

We present an extension of the research begun by Carlton (1995) into the effectiveness of reactive tabu search (RTS) on the multiple traveling salesman problem with time window constraints. We explore the application of this approach to the routing of unmanned aerial vehicles (UAVs) (Sisson 1997). Specifically, we offer three contributions in this area. First, from a formulation perspective we observe that UAV routing problems differ from those found in the general vehicle routing problem (GVRP) literature in two fundamental areas: (1) they possess unique stochastic characteristics, such as random winds and service times; and, (2) wind effect implies the travel time between any two nodes in the network is a function of travel direction. Second, from an implementation standpoint we merge the advantages of object-oriented simulation with Carlton's GVRP taxonomy and RTS algorithm in a way that provides a mechanism for rapid and extensive exploration of problems within the GVRP family. Finally, we identify UAV routes that are persistent throughout a simulation's state space, and show how this approach can provide a rudimentary assessment of the marginal utility of additional UAV platforms for a given reconnaissance scenario.

The paper is organized in a similar manner. We first introduce the relevant literature regarding the GVRP, present our formulation of the UAV problem, and provide a brief review of RTS. The next section describes our use of Carlton's GVRP taxonomy as the basis for designing the MODSIM-based RTS class libraries and inheritance structure, their use in Monte Carlo simulation, and code verification. We then present robust routing solutions for an operational reconnaissance scenario and an elementary marginal utility analysis of UAV fleet size.

UAV PROBLEM DESCRIPTION

The General Vehicle Routing Problem

Carlton's (1995) survey of proposed classification schemes of problems within the GVRP class found no prior systematic exploration or unifying description of the relationships among the problems of the GVRP family. Therefore, he proposes a hierarchical taxonomy that classifies the GVRP into three "floors" (TSP, VRP, and PDP) as shown in Figure 1. The first floor represents the family of *traveling salesman problems* (TSPs), with each row and column representing the presence or absence of a unique qualitative variation of the TSP. These qualities include the availability of a single vehicle (SV), multiple homogenous vehicles (MVH), or multiple non-homogenous vehicles ($M\bar{V}H$); single depot (SD) or multiple depots (MD); time window constraints present (TW); and, route length constraints present (RL) as shown in Figure 2. (Notationally, the symbol "—" represents the absence of a singular qualitative characteristic such as time windows or route length constraints.) The second floor, by inheriting the organizational structure of the TSP floor and adding vehicle capacity constraints, represents *vehicle routing problems* (VRPs). Similarly, overlaying precedence constraints extends the VRP class to the third floor of *pickup and delivery problems* (PDPs). Under this framework, then, each row-column combination of TSP attributes has a direct counterpart in the VRP and PDP domains.

The nature of the UAV reconnaissance mission is information transmission, and as such may have capacity (bandwidth) and precedence constraints, or require unique reconnaissance capabilities for individual vehicles within the UAV fleet. However,

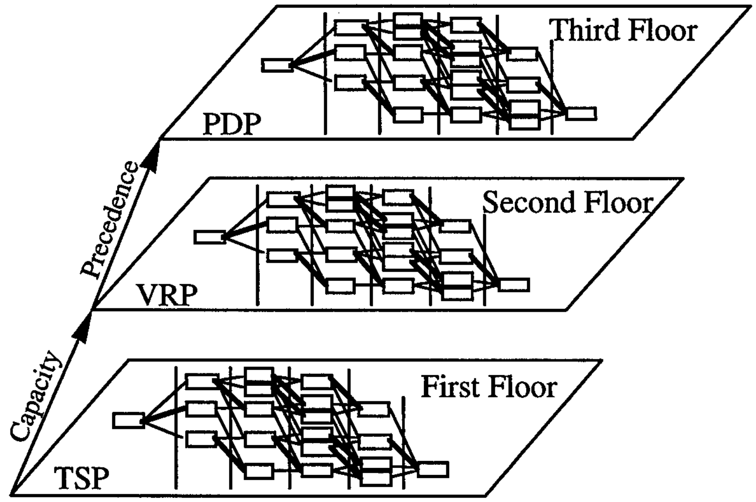

Figure 1. GVRP Hierarchical Classification Scheme (Carlton 1995).

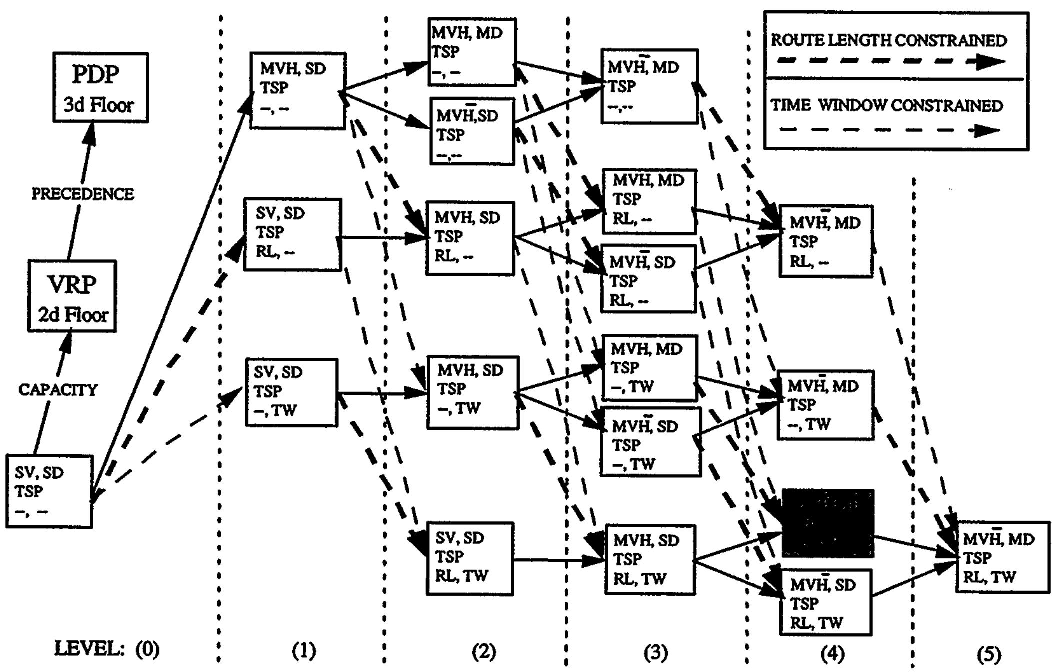

Figure 2. Traveling Salesman Problem Hierarchy; GVRP First Floor (Carlton 1995). (Label format: Single (SV) or multiple (MVH) vehicles, single (SD) or multiple (MD) depots, traveling salesman problem (TSP), route length (RL) constrained, and time window (TW) constrained.)

these considerations are not applicable in the mission profile we evaluated. Therefore, under Carlton's taxonomy we classify the UAV Problem (UAVP) as a traveling salesman problem, and assume the UAVs possess identical reconnaissance capability. Since UAV missions typically operate from a single airfield we restrict our model to a single depot, and further assume route length constraints apply since they arise naturally due to the UAV's limited total flight time. Finally, since one or more reconnaissance targets may require surveillance at specific times we include time windows. According to the hierarchical notation in Figure 2,

the UAVP is a homogenous multiple-vehicle, single-depot, traveling salesman problem with route length constraints and time windows [MVH,SD,TSP,RL,TW].

We conclude this section with two observations. First we note that, computationally, the GVRP falls in the NP-Complete set of combinatorial optimization problems (see Nemhauser and Wolsey 1988, Garey and Johnson 1979). Therefore, following Christofides (1985) approach of using heuristic methods to find "near-optimal" solutions to the GVRP, we employ Carlton's RTS method as our primary algorithm. Second, the organizational structure of Carlton's taxonomy (Figures 1–2) provides an outline for translating his RTS code into an inheritance structure common to object-oriented programming languages. This inheritance framework easily provides for a large degree of code reuse throughout the entire GVRP realm. An example of this ease of implementation is presented in the later section on object-oriented programming.

UAV Problem Formulation

Our formulation of the UAV problem (UAVP) is derived from a [MVH,SD,TSP,RL,TW] baseline. Following Carlton (1995), our RTS seeks *near-optimal* solutions to a [MVH, SD,TSP,RL,TW] with nc customers, indexed by i or j, each requiring a service time s_i. (In the context of the UAVP, the terms *target* or *target node* represent a *customer*.) The starting depot is designated 0, and the terminal depot by $nc + 1$. Given nv vehicles, if no feasible solutions are found after a reasonable search, we increase nv and restart the search. The time window for each customer i's pick up is (e_i, l_i), where e_i is the earliest possible arrival time and l_i is the latest. The early arrival time is treated as a "soft" constraint; i.e., vehicles arriving before e_i may wait until e_i is reached. W_i is the wait time at customer i. The parameter $t_{i,j}$ is the travel time from customer i to customer j. The binary decision variable $x^v_{i,j}$ equals 1 if vehicle v travels on the arc between customers i and j; otherwise it is 0. Tour schedule variables A_i and T_i indicate the time a vehicle arrives at customer i and the time service starts at customer i, respectively. The time windows, times between nodes, and service times are truncated to be integer for computational efficiency. Formally, we express the baseline [MVH,SD,TSP,RL,TW] as

$$\text{MIN } Z_t = \sum_{i=1}^{nc} \sum_{j=1}^{nc} \sum_{v=1}^{nv} x^v_{i,j} \cdot t_{i,j} \tag{1}$$

{Minimize total travel time}

Subject To:

$$\sum_{i=0}^{nc} \sum_{v=1}^{nv} x^v_{i,j} = 1 \quad \forall j = 1..nc$$

{One vehicle enters per customer}

$$\sum_{j=1}^{nc} \sum_{v=1}^{nv} x^v_{i,j} = 1 \quad \forall i = 0..nc$$

{One vehicle leaving per customer}

$$x^v_{i,j} \in \{0, 1\}$$

$$\forall i = 0..nc, \quad j = 1..nc, \quad v = 1..nv,$$

{Non-negativity constraint}

$$x^v_{i,j} = 1 \Rightarrow t_i + s_i + t_{i,j} + W_j = T_j$$

{Time precedence}

$$e_i \le T_i \le l_i \quad \forall i = 1..nc$$

{Time windows}

$$W_i = T_i - A_i \quad \forall i = 1..nc$$

{Waiting times}

$$\sum_{i=0}^{nc} x^v_{i,i} = 0 \quad \forall v = 1..nv$$

{Vehicle must serve different adjacent nodes}

$$\sum_{i=0}^{nc} x^v_{i,j} = \sum_{\substack{k=0 \\ k \neq j}}^{nc} x^v_{j,k} \quad \forall j = 1..nc, \forall v = 1..nv$$

$$\left\{ \begin{array}{c} \text{Same vehicle entering a node must exit;} \\ \text{routes cannot terminate at a customer} \end{array} \right\}$$

Additionally, given T^v as the maximum time a vehicle can be used, route length constraints are

defined and included as

$$\sum_{i=0}^{nc} \sum_{j=1}^{nc} x_{i,j}^{v} \cdot s_j + \sum_{i=0}^{nc} \sum_{j=1}^{nc} x_{i,j}^{v} \cdot W_j$$

$$+ \sum_{i=0}^{nc} \sum_{j=0}^{nc} x_{i,j}^{v} \cdot t_{i,j} \leq T^{v} \quad \forall v = 1..nv$$

$$\left\{\begin{array}{l}\text{Service time plus waiting times plus travel} \\ \text{time less than maximum vehicle usage time}\end{array}\right\}$$

Finally, let N designate the set of target nodes while D represents the set of starting and terminating depots. Where v indexes nv vehicles, let $N^v \subseteq N$ represent the nodes from N assigned to vehicle v such that for any vehicle v that is not used, $N^v = \emptyset$; $N^1 \cup N^2 \cup \ldots \cup N^{nv} = N$; and, where w also indexes nv vehicles, for all pairwise combinations of v and w such that $v \neq w$, $N^v \cap N^w = \emptyset$. The subtour breaking constraints, where $N_D^v = N^v \cup D$ for each $N^v \neq \emptyset$, are then defined and included in the model as

$$x_{ij}^{v}: \sum_{i \in Q} \sum_{j \neq Q} x_{ij} \geq 1$$

for every nonempty subset Q of N_D^v

$$\forall v = 1..nv.$$

{Prevent cycling in each tour}

The UAV problem modifies this [MVH, SD,TSP,RL,TW] formulation by first replacing the objective function (1) with an expected coverage function. Formally, coverage is defined as the number of targets that will be visited; therefore, the expected coverage of any single target equals the probability of surviving that target. Notationally, for target node n_i^v (the i^{th} target node visited in the route of vehicle v) the expected coverage is given by

$$\prod_{i=a^v}^{n_i^v} Ps(i)$$

where a^v is the starting node of vehicle v's tour, and $Ps(i)$ is the probability of survival at target node i. For instance, when a UAV travels from targets 1 to 2 to 3, and $Ps(1) = 0.9$, $Ps(2) = 0.8$, and $Ps(3) = 0.7$, the probability of "covering" target 1 is 0.9, target 2 is $(0.9) \cdot (0.8) = 0.72$, and target 3 is $(0.90) \cdot (0.80) \cdot (0.70) = 0.50$. Furthermore, the expected number of nodes covered along the route of vehicle v is given by the sum of the individual nodes' coverage; i.e.,

$$\sum_{n_i^v = a^v}^{b^v} \prod_{i=a^v}^{n_i^v} Ps(i) \tag{2}$$

where b^v is the ending node of vehicle v's tour and $a^v \leq n_i^v \leq b^v$. Thus, for the three node example above, the expected number of nodes covered is $0.90 + 0.72 + 0.50 = 2.12$.

In addition to the probability of survival at target node i ($Ps(i)$), a realistic representation of the operational reconnaissance environment requires characterizing target i service time s_i, and travel time between targets i and j ($t_{i,j}$), as random variables. The stochastic representation of s_i, which we denote as ω_i, captures the possibilities of a UAV extending its loitering time over target i due to unexpected enemy activity. Similarly, since UAVs fly at a constant indicated airspeed, ground speed—hence, travel time—will vary as a function of wind speed and direction. Formally, the random variable $\tau_{i,j}$ expresses the stochastic version of t_{ij}, which for each segment i,j is a unique random variable whose distribution is a function of the underlying bivariate distribution of wind speed and direction. Thus, the substitutions of s_i with ω_i and t_{ij} with $\tau_{i,j}$, and the replacement of the original objective function (1) with the objective of maximizing (2), defines the UAVP formulation. (When using (2) alone as the objective function the UAVP no longer considers minimizing routing criteria such as travel time and vehicle usage. Our implementation reintroduces this aspect of routing objectives at the end of the next section.)

In general, for any segment i,j under the s^{th} realization of wind speed and direction, $\tau_{i,j}^{s} \neq \tau_{j,i}^{s}$. Therefore, each realization of a wind vector requires recalculating travel times without the symmetry often assumed for ground-based routing problems. Furthermore, travel time calculations must also account for target locations that are operationally expressed in latitude and longitude. The angular difference D (at the earth's center) in radians between locations $x(x_{lat}, x_{long})$ and y (y_{lat}, y_{long}) is estimated using

the relationship

$$D = \cos^{-1}[\sin(x_{lat}) \cdot \sin(y_{lat}) + \cos(x_{lat}) \cdot \cos(y_{lat}) \cdot \cos(\text{abs}(y_{long} - x_{long}))]$$

and converted into nautical miles by equating one radian to 57.2958 degrees and one degree on the earth's surface to 60 nautical miles (Department of the Air Force 1983). The Law of Cosines must be used to calculate the travel time to account for the influence of a wind vector, and requires knowing ϕ, the angle between the heading (θ_{xy}), and the direction from which the wind originates (θ_w), where

$$\phi = \theta_w - \theta_{xy}.$$

The heading, when traveling from x to y, is given by

$$\theta_{xy} = \sin^{-1}\left(\frac{y_{lat} - x_{lat}}{D}\right)$$

$$\text{when} \quad y_{long} - x_{long} \geq 0, \quad \text{and}$$

$$\theta_{xy} = 180° - \sin^{-1}\left(\frac{y_{lat} - x_{lat}}{D}\right)$$

$$\text{when} \quad y_{long} - x_{long} < 0.$$

Since UAV operators receive the wind's heading as a compass direction, converting compass heading θ_w^c to Cartesian coordinate system of θ_{xy} is given as

$$\theta_w = (360 - \theta_w^c) + 90°.$$

The ground speed (GS) is estimated as

$$GS^2 = AS^2 + WS^2 - 2 \cdot AS \cdot WS \cdot \cos(\phi)$$

where AS is the UAV airspeed and WS is the magnitude of the wind vector or wind speed. Finally, the division of D by GS, where D and GS are specified in the same units of distance, yields the time to travel from x to y.

Reactive Tabu Search

We begin by noting that tabu search (TS) (Glover 1989, 1990a,b; Glover and Laguna 1997) is a heuristic for providing excellent solutions to hard combinatorial problems by moving from one solution to another in a way that avoids becoming trapped in local optimal solutions. Through the use of flexible memory, mechanisms for either constraining or relaxing the criteria used in the search process, and intensification and diversification, TS represents a logical application of adaptive, memory-based search strategies. TS records and reports the best solution discovered during its search, and often this solution is optimal. It is important to note, however, that TS does not guarantee finding an optimal solution—it will neither recognize an optimal solution, or terminate the search if it encounters one. (Our literature review focuses on TS applications in a GVRP context, and assumes a working knowledge of basic TS procedures and terminology. We refer the interested reader to the above references for additional background.)

The literature identifies TS—and a variant called *reactive tabu search* (RTS)—as powerful heuristics for the GVRP. Laporte (1992a,b) surveys the exact and heuristic algorithms for the TSP and VRP, giving the highest marks to TS. Potvin *et al.* (1996) compare the performance of their TS heuristic to that of five other documented heuristics upon the well-known Solomon (1987) datasets. Their TS employs a tabu list of fixed length and infeasible regions that are not accessible to the search, yet the quality of solutions reached by their version of TS outperforms the other heuristics considered except a genetic sectoring algorithm called GIDEON (Thangiah 1993).

Glover (1990a) suggests the use of a frequency-derived (the frequency of revisited solutions) penalty to encourage diversification. Battiti and Tecchiolli's (1994) work extends Glover's suggestion by showing RTS to be a far more robust procedure than fixed and strict tabu search heuristics. (RTS differs from TS in that the length of the tabu list "reacts" to the quality of the solutions found during the search.) Battiti (1996) demonstrates how RTS effectively overcomes the drawbacks of computationally expensive parameter tuning and defeats the confinement of the search to local optima so common to fixed or strict implementations of TS. In his four-bit (0/1) example illustrating the properties of RTS, Battiti found the tabu list length takes progressively more iterations to increase after the previous increment; furthermore, the distance of the search from the optimal "attractor" varies quickly while rapidly increasing to the maximum range. As a counter-example, Rochat and Tail-

lard (1995) rely heavily on randomization to overcome these weaknesses by generating a set of "good" simple TS solutions and then improving this set through a method reminiscent of genetic algorithms.

Carlton (1995) demonstrates how RTS removes the need for any pre-processing of the sort suggested by Glover, and shows the randomization techniques proposed by Rochat and Taillard are unnecessary. The de-emphasis of randomization is a central tenet of TS (Glover and Laguna 1993, 1997); and, although it requires greater computational effort, Carlton's wholly deterministic RTS implementation with an arbitrarily chosen initial solution consistently finds solutions of equal quality to those reached from feasible starting tours. By comparing his results to heuristics similar to the group compiled by Potvin *et al.* (1996), Carlton concludes that RTS dominates the others in solution quality, including GIDEON. Consequently, we adopt Carlton's RTS algorithm as the UAVP solver in the Monte Carlo simulation described in the next section. (Tables 1–3 describe the pseudocode for the RTS.)

Finally, we note that one drawback to this version of the UAVP is that routing criteria (e.g., travel time, vehicle usage) are no longer considered in the objective function. Sisson (1997) suggests using a linear combination of (1) and (2) as the objective function, with the decision-maker's level of risk tolerance determining the relative weights of the two principal components. Alternatively, we introduce a unique hierarchical structure in our tabu search that consistently seeks to maximize (2), but selects solutions of equal expected coverage based on minimal values of (1). Specifically, let k represent the current iteration of the RTS, T_k the incumbent tour of the k^{th} iteration, and $\mathcal{N}_{k+1}$ the set of non-tabu tours that are one move away from T_k (i.e., the non-tabu *neighborhood* of

Table 1. Main Module Diagram, mTSPTW.

	Mtsptw (ModSim main module)			
mTSPTW Reactive Tabu Search Pseudocode	**SOURCE**	**OBJECT**	**METHOD**	**PROCEDURE**
0. Initialize: Structures, vectors, parameters	(main)			
1. Input problem instance:	tsptwMod	timeMatrix	readCarlton	
a. # of iterations = niters / Input service times	(main)			
b. Compute time/distance matrix	tsptwMod	timeMatrix	timeMatrix	
2. Select the starting tour	tsptwMod	startTour	startTour	
a. Compute initial schedule	tabuMod	"	"	tourSched
b. Compute initial tour penalties	tabuMod	"	startPenBest	compPens
c. Given penalties, compute initial tour cost	tabuMod	"	"	tsptwPen
d. Compute the initial hashing values: f(T) and thv(T)	tabuMod	"	"	tourHVwz
e. Save as initial best solution	bestSolnMod	"	"	twBestTT
3. While (k <= niters)	tsptwMod	reacTabuObj	search	
a. Look for the incumbent tour in the hashing structure	hashMod	"	"	lookfor
1) If found, update the iteration when found, and increase the tabu length, if applicable	tabuMod	"	"	cycle
2) If not found, add to the hashing structure, and decrease the tabu length, if applicable	tabuMod	"	"	nocycle
b. Perform "later" insertions: I(i,d) for i = 1 to n-1, d >= 1	tabuMod	reacTabuObj	search	SwapNode
1) Calculate the penalties associated with an insertion	tabuMod	"	"	compPens
2) Calculate the value of making this insertion	tabuMod	"	"	moveValTT
c. Evaluate all "earlier" insertions: I(i,d) for i = 3 to n, d <= -2	"	"	"	"
d. Move to the non-tabu neighbor according to an appropriate decision criteria. If all tours are tabu, move to the neighbor with the smallest move value, and reduce the tabu length	tabuMod	reacTabuObj	search	insert
e. Update the search parameters:				
1) Incumbent tour schedule	tabuMod	"	"	tourSched
2) Incumbent tour hashing value	tabuMod	"	"	tourHVwz
3) Retain the best feasible solution found and the tour with the smallest tour cost regardless of feasiblity	bestSolnMod	"	"	twBestTT
f. Increase iteration count: k = k+1	tsptwMod	reacTabuObj	search	
4. Output Results	tabuMod			twLoadToFile

Directions: To find where a portion of the pseudocode is executed, one can read the OBJECT, METHOD, and PROCEDURE columns like a hierarchical path name. The heading "(main)" indicates the implementation code can be found in the main module. Dark gray spaces indicate that space's depth in the hierarchy is unneeded to specify the location and " indicates the reference is identical to the last entry above it.

Table 2. Main Module Diagram (mTSPTW with Winds).

mTSPTW (Winds Included) RTS Pseudocode	MUAV (ModSim main module) SOURCE	OBJECT	METHOD	PROCEDURE
0. Initialize: Structures, vectors, parameters	(main)			
1. Input problem instance:	tsptwMod	timeMatrix	readProblem	
a. # of iterations = niters / Input service times	(main)			
b. Compute 'no wind' distance matrix	UAVMod	timeMatrix	distMatrix	
c. Compute the time matrix with winds	UAVMod	timeMatrix	timeMatrix	
2. Select the starting tour	tsptwMod	startTour	startTour	
a. Compute initial schedule	tabuMod	"	"	tourSched
b. Compute initial tour penalties	tabuMod	"	startPenBest	compPens
c. Given penalties, compute initial tour cost	tabuMod	"	"	tsptwPen
d. Compute the initial hashing values: f(T) and thv(T)	tabuMod	"	"	tourHVwz
e. Save as initial best solution	bestSolnMod	"	"	twBestTT
3. While (k <= niters)	tsptwMod	reacTabuObj	search	
a. Look for the incumbent tour in the hashing structure	hashMod	"	"	lookfor
1) If found, update the iteration when found, and increase the tabu length, if applicable	tabuMod	"	"	cycle
2) If not found, add to the hashing structure, and decrease the tabu length, if applicable	tabuMod	"	"	nocycle
b. Perform "later" insertions: I(i,d) for i = 1 to n-1, d >= 1	tabuMod	reacTabuObj	search	SwapNode
1) Calculate the penalties associated with an insertion	tabuMod	"	"	compPens
2) Calculate the value of making this insertion	tabuMod	"	"	moveValTT
c. Evaluate all "earlier" insertions: I(i,d) for i = 3 to n, d <= -2	"	"	"	"
d. Move to the non-tabu neighbor according to an appropriate decision criteria. If all tours are tabu, move to the neighbor with the smallest move value, and reduce the tabu length	tsptwMod	reacTabuObj	search	insert
e. Update the search parameters:				
1) Incumbent tour schedule	tabuMod	"	"	tourSched
2) Incumbent tour hashing value	tabuMod	"	"	tourHVwz
3) Retain the best feasible solution found and the tour with the smallest tour cost regardless of feasiblity	tsptwMod	"	"	twBestTT
f. Increase iteration count: k = k + 1	tsptwMod	reacTabuObj	search	
4. Output results	tsptwMod			twLoadToFile

Directions: To find where a portion of the pseudocode is executed, one can read the OBJECT, METHOD, and PROCEDURE columns like a hierarchical path name. The heading "(main)" indicates the implementation code can be found in the main module. Dark gray spaces indicate that space's depth in the hierarchy is unneeded to specify the location and " indicates the reference is identical to the last entry above it. Light gray spaces identify code that differs from the original mTSPTW formulation.

T_k). Furthermore, let n represent the size of $\mathcal{N}_{k+1}$ where tour $T(i)_{k+1} \in \mathcal{N}_{k+1}$ for $i = 1, \ldots, n$. Where $F_1(\bullet)$ and $F_2(\bullet)$ evaluate tour values using the objective functions (1) and (2), respectively, let $C(i)_{k+1} = F_2(T(i)_{k+1})$, and re-index i as i_c such that the set $\mathcal{V}_{k+1}$ represents the tours in $\mathcal{N}_{k+1}$ ordered by their expected coverage; i.e.,

$$C(1_c)_{k+1} \leq C(2_c)_{k+1} \leq, \ldots, \leq C(i_c)_{k+1} \leq, \ldots, \leq C(n_c)_{k+1} \quad (3)$$

and

$$\mathcal{V}_{k+1} = \{T(1_c)_{k+1}, T(2_c)_{k+1}, \ldots, T(i_c)_{k+1}, \ldots, T(n_c)_{k+1}\}.$$

Similarly, let $R(i)_{k+1} = F_1(T(i)_{k+1})$, and re-index i as i_r such that the set $\mathcal{R}_{k+1}$ represents the tours in $\mathcal{N}_{k+1}$ ordered by their total travel time; i.e.,

$$R(1_r)_{k+1} \leq R(2_r)_{k+1} \leq, \ldots, \leq R(i_r)_{k+1} \leq, \ldots, \leq R(n_r)_{k+1}$$

and

$$\mathcal{R}_{k+1} = \{T(1_r)_{k+1}, T(2_r)_{k+1}, \ldots, T(i_r)_{k+1}, \ldots, T(n_r)_{k+1}\}. \quad (4)$$

Using the above definitions, our RTS selects $T(1_c)_{k+1}$ as the next tour T_{k+1} whenever $C(1_c)_{k+1}$ is strictly less than $C(2_c)_{k+1}$, and regardless of the order of $T(1_c)_{k+1}$ in $\mathcal{R}_{k+1}$; i.e., the best tour in terms of coverage. However, if there exists an integer j such that $1 < j \leq n$ for the largest

Table 3. Main Module Diagram (UAV).

UAV Reactive Tabu Search Pseudocode	MUAV (ModSim main module) SOURCE	OBJECT	METHOD	PROCEDURE
0. Initialize: Structures, vectors, parameters	(main)			
1. Input problem instance:	tsptwMod	timeMatrix	readProblem	
a. # of iterations = niters / Input service times	(main)			
b. Compute 'no wind' distance matrix	UAVMod	timeMatrix	distMatrix	
c. Compute the time matrix with winds	UAVMod	timeMatrix	timeMatrix	
2. Select the starting tour	tsptwMod	startTour	startTour	
a. Compute initial schedule	tabuMod	"	"	tourSched
b. Compute initial tour penalties	tabuMod	"	startPenBest	compPens
c. Given penalties, compute initial tour cost	tabuMod	"	"	tsptwPen
d. Compute the initial hashing values: f(T) and thv(T)	tabuMod	"	"	tourHVwz
e. Save as initial best solution	bestSolnMod	"	"	twBestTT
3. While (k <= niters)	UAVMod	uavRTSobj	search	
a. Look for the incumbent tour in the hashing structure	hashMod	"	"	lookfor
1) If found, update the iteration when found, and increase the tabu length, if applicable	tabuMod	"	"	cycle
2) If not found, add to the hashing structure, and decrease the tabu length, if applicable	tabuMod	"	"	nocycle
b. Perform "later" insertions: I(i,d) for i = 1 to n-1, d >= 1	UAVMod	uavRTSobj	search	SwapNode
1) Calculate the penalties associated with an insertion	tabuMod	"	"	compPens
2) Calculate the value of making this insertion	UAVMod	"	"	expCvrg
c. Evaluate all "earlier" insertions: I(i,d) for i = 3 to n, d <= -2	"	"	"	"
d. Move to the non-tabu neighbor according to an appropriate decision criteria. If all tours are tabu, move to the neighbor with the smallest move value, and reduce the tabu length	tabuMod	uavRTSobj	search	insert
e. Update the search parameters:				
1) Incumbent tour schedule	tabuMod	"	"	tourSched
2) Incumbent tour hashing value	tabuMod	"	"	tourHVwz
3) Retain the best feasible solution found and the tour with the smallest tour cost regardless of feasiblity	bestSolnMod	"	"	twBestTT
f. Increase iteration count: k = k + 1	UAVMod	uavRTSobj	search	
4. Output results	UAVMod			twCvrgToFile

Directions: To find where a portion of the pseudocode is executed, one can read the OBJECT, METHOD, and PROCEDURE columns like a hierarchical path name. The heading "(main)" indicates the implementation code can be found in the main module. Dark gray spaces indicate that space's depth in the hierarchy is unneeded to specify the location and " indicates the reference is identical to the last entry above it. Light gray spaces identify code that differs from the original mTSPTW formulation.

possible value of j, and $C(1_c)_{k+1} = C(j_c)_{k+1}$, then the RTS selects $T(i_r)_{k+1}$ as the next tour T_{k+1}, where i_r identifies the lowest order element in $\mathfrak{R}_{k+1}$ such that $T(i_r)_{k+1} = T(i_c)_{k+1}$ and $1 \leq i_c \leq j$; i.e., the best tour in terms of the total travel time of those tours tied for best coverage.

IMPLEMENTATION

Object-Oriented Programming

Object-oriented (OO) programming languages facilitate the inheritance and reuse of object definitions and methods (see Kassou and Pecuchet 1994). We make full use of this approach by using CACI's OO language MODSIM (CACI 1996) as our language of implementation. In MODSIM, each object contains its own data (fields) and routines (methods) and is structured such that while data in its fields can be read by other objects, they can only be modified by the object's own internal methods. The inheritance capability of OO programming enables new classes to be created from existing classes by inheriting the fields and methods of the existing classes. The new class can then redefine (or override) the inherited methods to behave differently, as well as incorporate new fields and methods.

This encapsulation characteristic of OO programming is useful in solving the GVRP in that it allows different objective functions to be efficiently introduced to a RTS solver. Such inheritance and reuse advantages motivate our translating Carlton's (1995) C language code into a set of MODSIM classes from which we *instantiate* (i.e., create) an RTS object for solving

the UAVP. These classes provide a "core" solver for the [MVH,SD,TSP,RL,—] and [MVH, SD,TSP,RL,TW] members of the GVRP family. The RTS object can then solve the UAVP using the inheritance feature and making the minor adjustments described below. (For clarity and consistency with the literature, we use the slightly less precise notation of MTSPTW (**m**ultiple-vehicle **T**raveling **S**alesman **P**roblem with **T**ime **W**indows) when describing the MODSIM class designed for solving the [MVH,SD,TSP, RL,TW] formulation of the TSP.)

Table 1 depicts the MODSIM structure of libraries and classes designed to solve MTSPTW problems. The pseudocode corresponds to the OBJECT, METHOD, and PROCEDURE columns in a hierarchical fashion similar to a path name. The heading (*main*) indicates the implementation code can be found in the main module. In all cases, one follows the path to find the physical location of the code in the right-most nonblank space. If the code is not in the main module, the library listed is the one in which the right-most nonblank identifier lies. Dark gray spaces indicate those portions of the hierarchy are unnecessary in specifying the location.

The libraries provide a general framework for categorizing code into areas of similarity. Here, *tabuMod* contains code for use in GVRP-related tabu heuristics. The modules of *tsptwMod* contain code tailored for the mTSPTW and UAVP, and *hashMod* holds the code for the creation and use of the hashing structure. (Solutions often share the same objective function value; therefore, additional solution attributes must be retained in order to differentiate among such solutions. A hashing structure is one such approach that allows the TS to recognize when a current solution has already been visited in order to minimize the probability of two distinct tours being incorrectly treated as identical.) As noted by Carlton (1995), many different objective functions can be used for GVRP problems, so *bestSolnMod* separates the code determining the best solution visited.

Tailoring the MTSPTW code for the UAVP is straightforward. Random service times are modeled using the same main module for the MTSPTW problem of Table 1. The light gray boxes in Table 2 illustrate the changes necessary to include random winds into the problem. (Specifically, both the distance and time matrices are recalculated to account for changes in wind direction and speed. We further note that our code assumes the same wind component, once determined by the simulation, applies to each leg. However, the modular structure of MODSIM allows for the future inclusion of weather models that provide more realistic wind patterns.) Table 3 depicts the MODSIM code and RTS pseudocode when threats are modeled and we seek to maximize coverage. Since the UAV class is essentially a MTSPTW class with an altered objective function, we take advantage of the inheritance and polymorphism qualities of MODSIM by substituting only those portions of our MTSPTW associated with the move evaluation. Except for the lightly grayed-in areas, Table 3 is identical to the mTSPTW code in Table 1.

Verification

We verified our RTS class using three independent methods. First, we stepped through the translated code line-by-line with a 4-city TSP problem, and compared and evaluated its performance with the known optimal solution. Second, using the notation presented earlier in Figure 2, the RTS object can solve the [SVH, SD,TSP,—,—] and [MVH,SD,TSP,—,—] TSPs by reading in time window widths far exceeding the tour length of any feasible solution and setting every node's load quantity to zero. Thus, we further verified the heuristic's capabilities with the TSP by comparing its results to a 10-city TSP (Moore 1997) of known optimal solution (which was found on iteration 288 as shown in Figure 3). (We note the peaks and valleys of tabu length and correlated tour length, shown in Figure 3, confirms the RTS alternatively employs diversification and intensification search strategies.) Finally, we conducted a direct comparison of Carlton's (1995) results on 26 selected problems from Solomon (1987) and RTS found better solutions for all but one (Table 4). We attribute the few differences in solution quality to the two distinct computational environments.

Simulation

Using the portable quality of our MODSIM classes, we instantiate (i.e., create) an RTS object from the UAVP class (Table 3) and embed it in a Monte Carlo simulation to capture the variability of the operational environment's parameters. We accomplish this by creating a scenario

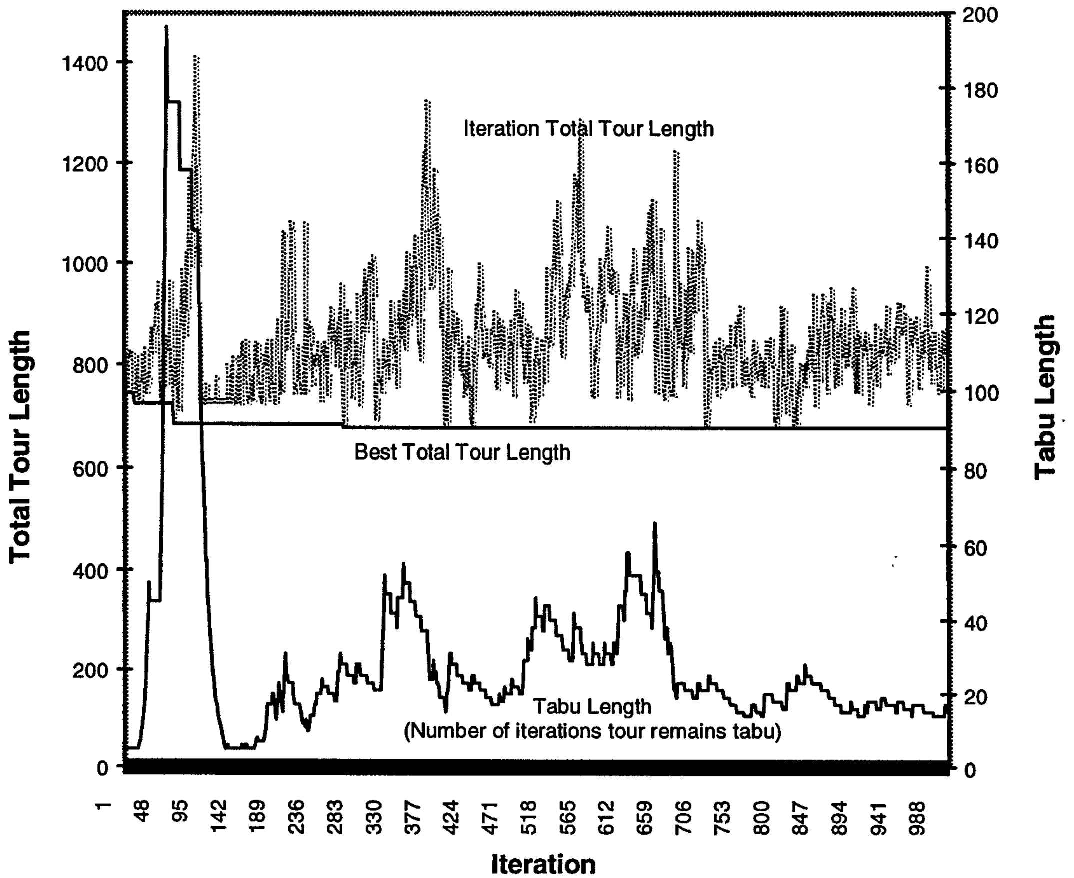

Figure 3. Ohio 10-City Problem.

at each replication of the simulation, each having a unique realization of wind magnitude and direction, vehicle survival rates, and target service times. Then, beginning with an arbitrary solution, the RTS object finds the best routing solution for that particular scenario. When the RTS for the current replication's scenario ends (i.e., the specified number of tabu search iterations have been accomplished), a new set of realizations of the random variables are generated for the scenario used in the simulation's next replication. The RTS object then begins its search starting with the best solution of the just-completed scenario; in this manner the previous routing solution serves as a naïve forecast of the next one. When the search completes the last scenario, the frequencies of routes used in the feasible solutions are summed in a route frequency matrix. The replication whose solution contains those routes that are most persistent (i.e., those whose sum of route frequencies is the greatest) we term the *robust tour.*

BOSNIA SCENARIO ANALYSIS

The scenario we analyze is a notional set of Bosnia reconnaissance targets (Table 5, Figure 4) provided by the 11th Reconnaissance Squadron (Bergdahl 1998). This operationally representative data consists of target locations specified in latitude and longitude; time windows (21 targets must be visited twice); and, required service (loiter) time at each target (the same service times apply to twice-visited targets). Targets requiring a second visit ("Dumdvga" through "Dromada Warehouse") are modeled as two independent nodes. For this particular scenario target threats are minimal; thus, with

Table 4. TSPTW Results.

Problem Name	Solution	# Vehicles Used	Iteration # Of Best Solution	Time of Best Solution (secs)
5 Vehicles Available, 1000 Iterations Performed				
C101	2441.3	3	23	5
C102	2440.3	3	153	42
C103	2436.9	3	77	25
C104	2441.3	3	611	237
C105	2441.3	3	195	51
C106	2441.3	3	26	5
C107	2441.3	3	28	6
C108	2441.3	3	489	138
C109	2441.3	3	190	58
10 Vehicles Available, 1000 Iterations Performed				
R101	867.1	8	144	36
R102	797.1	7	34	9
R103	704.6	5	135	47
R104	666.9	4	85	33
R105	780.5	6	94	25
R106*	721.1	5	31	9
R107**	674.3	4	871	343
R108	647.3	4	58	23
R109	691.3	5	32	9
10 Vehicles Available, 1000 Iterations Performed				
RC101	711.1	4	341	87
RC102	601.7	3	20	6
RC103	583.0	3	226	78
RC104**	556.6	3	466	180
RC105	661.2	4	145	38
RC106	595.5	3	144	40
RC107	548.8	3	27	9
RC108	544.5	3	675	284

* Carlton found a better solution (715.4) on iteration 1,209.

** Optimal Solution found. Carlton did not find an optimal solution for these instances.

target survival probabilities set to 1.0 expected coverage for all tours equals the number of targets. In terms of (3), for the Bosnia scenario we have

$$C(1_c)_{k+1} = C(2_c)_{k+1} = , \ldots , = C(i_c)_{k+1} = , \ldots , = C(n_c)_{k+1}$$

for all tours. Therefore, the minimum travel time solution $T(1_c)_{k+1}$ described in (4) is always selected as the next tour T_{k+1}. (For scenarios where vehicle survival probabilities less than 1.0 are modeled see Sisson 1997 and Ryan *et al.* 1998.)

The data set is clustered as targets into three remote operating zones (ROZ) based on one of three "first visit" time windows: 1015–1500, 1500–1715, or 1730–1830. Winds vary between 265 and 315 degrees in origin at a magnitude ranging between 10 and 25 knots. Each target is given a 0.3 probability of its service time increasing above its minimum level; for those targets whose service times are randomly increased, the total service time is modeled as uniformly distributed on the range of individual service times given in Table 5. (This aspect of the model reflects the operational fact that each target requires a minimum surveillance period (i.e., its minimum service time) to determine if it warrants further observation. Since a variety of reasons can necessitate extended inspection or loitering, we assume a variety of service times—with no central tendency—will occur after the initial target survey for 3 out of 10 targets.) For operational reasons the maximum time aloft (i.e, route length constraint) for each UAV is 23.75 hours. However, since this

Table 5. National Bosnia Data.

	R			Latitude			Longitude			First Visit		Service Time		Second Visit	
Target Name	O Z	#1 ID	#2 ID	Deg	Min	Sec	Deg	Min	Sec	Early Arrival	Late Arrival	Ranges (min)		Early Arrival	Late Arrival
Taszar Hungary, Depot				46	24	0	17	54	0						
Corridor, Szulok Hungary				46	3	45	17	32	44						
Corridor, Srbac Bosnia				45	24	0	17	30	0						
Dumdvga	1	1	32	44	58	29	16	50	34	1015	1500	30	180	1900	2300
Mastye	1	2	33	44	58	46	16	38	56	1015	1500	30	180	1900	2300
Garred AAA Site	1	3	34	44	58	4	16	39	31	1015	1500	2	15	1900	2300
Tharmet Heavy Weapons Depot	1	4	35	44	58	33	16	39	18	1015	1500	2	30	1900	2300
Tharmet Heavy Weapons Depot	1	5	36	44	58	39	16	39	41	1015	1500	2	30	1900	2300
Tharmet Heavy Weapons Depot	1	6	37	44	58	59	16	39	28	1015	1500	2	30	1900	2300
Serdona Communications Site	1	7	38	44	59	2	16	39	56	1015	1500	2	30	1900	2300
Serdona Communications Site	1	8	39	44	59	11	16	40	19	1015	1500	2	30	1900	2300
Serdona Communications Site	1	9	40	44	59	15	16	39	20	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	10	41	44	59	9	16	39	10	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	11	42	44	54	52	16	34	47	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	12	43	44	51	49	16	41	37	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	13	44	44	0	7	16	34	47	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	14	45	44	59	9	16	49	17	1015	1500	2	30	1900	2300
Suspected Weapons Storage	1	15	46	44	57	41	16	39	35	1015	1500	2	30	1900	2300
Air Defense, SAM, Probable SA-2	1	16	47	44	57	23	16	51	45	1015	1500	2	30	1900	2300
Air Defense, SAM, Probable SA-2	1	17	48	44	57	45	16	49	28	1015	1500	2	30	1900	2300
Air Defense, SAM, Probable SA-2	1	18	49	44	55	57	16	43	52	1015	1500	2	30	1900	2300
Air Defense, SAM Site Radar	1	19	50	44	57	47	16	39	54	1015	1500	2	30	1900	2300
Dromada HQ Site	1	20	51	45	0	7	16	53	49	1015	1500	30	120	1900	2300
Dromada Warehouse	1	21	52	44	53	31	16	54	12	1015	1500	2	60	1900	2300
Omanski Barracks	2	22		44	45	34	17	10	34	1015	1715	5	120		
Omanski Barracks	2	23		44	48	19	17	12	14	1015	1715	5	120		
Omanski Barracks	2	24		44	51	2	17	13	24	1015	1715	5	120		
Bolstavec Tank Rally Point	2	25		44	50	51	17	14	39	1015	1715	2	30		
Bolstavec Tank Rally Point	2	26		44	56	17	17	17	41	1015	1715	2	30		
Krajachastane Storage Bunker	2	27		44	55	51	17	17	51	1015	1715	2	30		
Krajachastane Storage Bunker	2	28		44	56	7	17	18	23	1015	1715	2	30		
Goldprtunity Road	3	29		44	28	13	17	1	18	1015	1830	20	40		
Goldprtunity Road	3	30		44	27	29	17	1	46	1015	1830	20	40		
Goldprtunity Road	3	31		44	27	10	17	2	24	1015	1830	20	40		

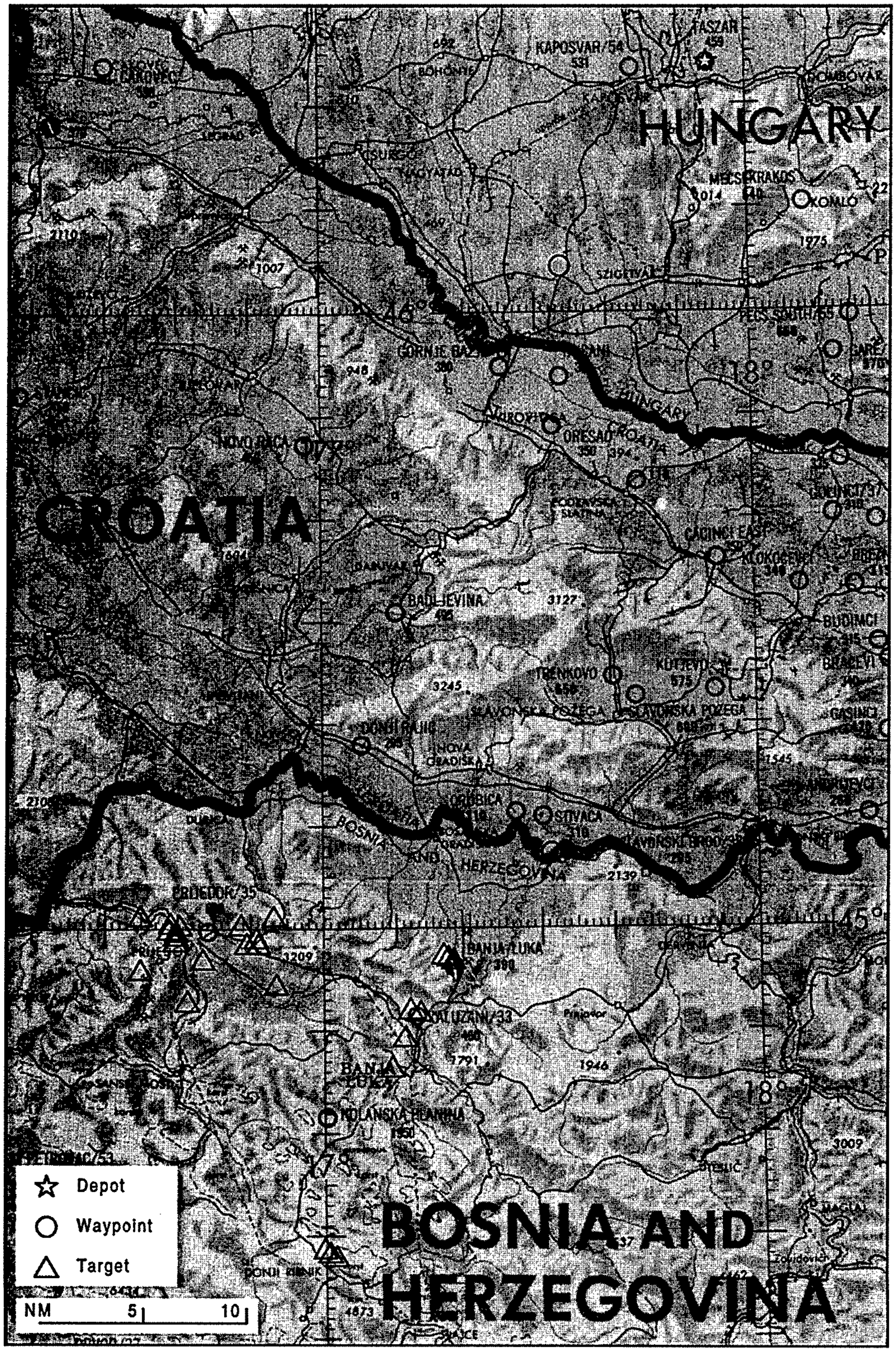

Figure 4. Bosnia Scenario Target Locations.

restriction is not a physical constraint, we allow the tabu search to consider solutions whose tours exceed 23.75 hours in order to accommodate operator judgment on flight time extensions. Finally, five UAVs are available for use and assumed to be 100% operational.

Our objective is to identify robust routing for any given day; therefore, we base our analysis on the simulation of 21 days, where each day represents one independent replication of a single 24-hour scenario. Each replication resets the number of UAVs on hand to the maximum available, generates an independent realization of winds and threat, and sets the RTS search at 500 iterations. Our choice of 21 days represents a subjective tradeoff between a reasonable sampling of all the possible wind and threat environments, and simulation run time.

The first of two analytical objectives is to find a routing schedule, or tour, that first maximizes expected target coverage, then minimizes total travel time, under most wind and threat conditions; i.e., a *robust tour.* Figure 5 graphically depicts the best tour found by the RTS for each day of the 21-day simulation. (The Taszar UAV depot lies in the upper right-hand corner. Furthermore, note that our use of the term "depot" should not be confused with the Tharmet *weapons* depots in the target list of Table 5. Throughout our narrative the term "depot" refers to the departure and return location of the UAVs.) Although the shapes of the tours do not readily yield to a visual examination, based on the following frequency analysis Day 16 contains those tours that appear most often over the 21-day simulation.

A frequency analysis can be more readily conducted by using a route frequency matrix, which in turn requires understanding the RTS solution vector. The notional example of a solution vector in Figure 6 is a TSP of four targets (numbered 1–4), four vehicles (0,5–7), and one depot (8) represented as geometric figures (circles for targets, squares for vehicles). Using this format, *the targets (in circles) between two vehicles (in squares) represent the nodes and the order in which the vehicle that immediately precedes them visits them.* In this notional case, Vehicle 0 is routed Depot—Target 1—Target 2—Depot, Vehicle 5 travels Depot—Target 3—Target 4—Depot, and the remaining two vehicles (6 and 7) are idle since there are no targets between them and the next vehicle node. (We note that from this perspective a RTS move is a change in the order of the incumbent tour array.) Another example of the RTS solution vector is given in Table 6, which shows the RTS solution vector for the robust tour of Day 16. Vehicle 0 starts at Target 20 and finishes at Target 51 after covering 23 nodes in 22.03 hours; the second UAV, Vehicle 53, begins at Target 26 and finishes at Target 47 after covering the remaining 29 targets in 22.22 hours. The highlighted number in the *Simulation Results Arrival* column indicates that this particular solution requires the operator to extend the 23.75-hour limit by 0.46 hours (27.6 minutes). Additionally, the highlighted numbers in the *Simulation Results Service Time* column show where actual service times exceed their respective minimum input service parameters, thus representing those occasions where the simulation emulates targets requiring expanded surveillance.

Figure 7 displays the route frequency matrix of the Bosnia simulation. The row labels represent the departure node *i*, the column labels the arrival node *j*, and the contents of the corresponding cell denote the number of days that particular segment was part of the solution tour. Specifically, there is a single depot (labeled 57), 52 targets (the 21 targets starting with "Dumdvga" through "Dromada Warehouse" that count twice, plus the ten remaining targets "Omanski Barracks" through "Golprtuniy Road", are labeled 1–52), and five UAVs (labeled 0, 53–56 and shaded light gray to distinguish them from target nodes).

The frequency matrix provides several levels of information, beginning with vehicle utility. For instance, reading across the first row (labeled '0') shows that Vehicle 0 is used in all 21 replications (the row sum); in nine of them its initial destination is Target 8; two replications send it to Target 14 first, while the remaining ten scenarios begin its route with Target 20. Similarly, the row for Vehicle 53 indicates that out of 21 replications its first destination is Target 9 twice, Target 14 once, Target 20 five times, Target 26 six times, and Target 28 four times. The remaining three replications show it adjacent to Vehicle 54 in the

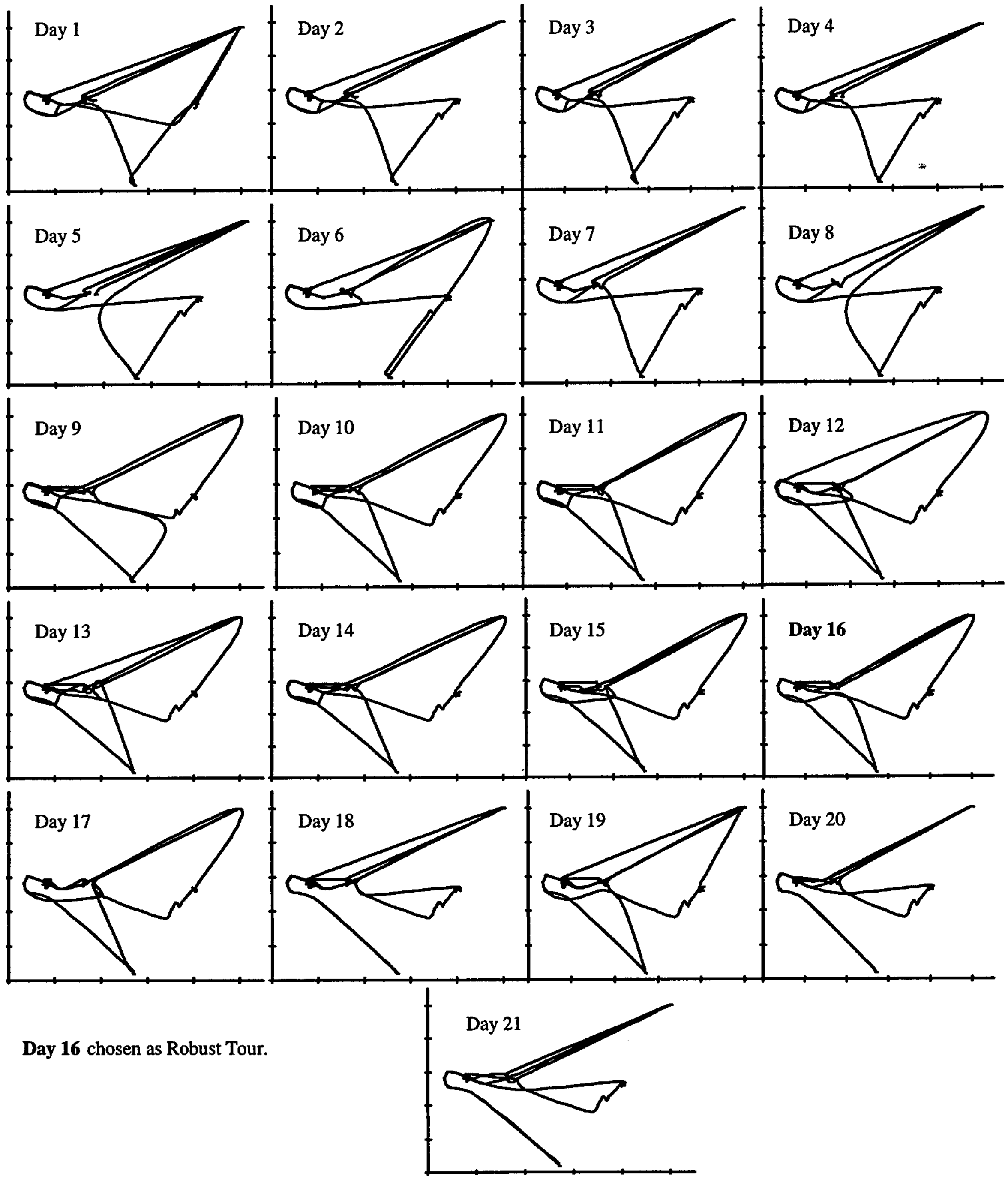

Figure 5. Tours Chosen for Bosnia Scenarios.

solution vector, thus denoting that it is not used on those days. Applying this interpretation to the remaining three UAVs shows that VEHICLE 54 is used in only five replications (with all five tours starting with TARGET 20), and VEHICLES 55–56 are never utilized. Said another way, the simulation suggests that at most only three UAVs are needed for this scenario, and for the

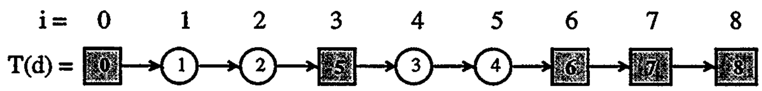

Figure 6. Notional Tour Array.

majority of modeled weather and threat realizations two aircraft will suffice.

Information from a matrix of this type is 'one-deep'—we cannot determine the complete sequence of targets for any single vehicle for any single route. For instance, while VEHICLE 0 starts with TARGET 8 in nine of the replications, row 8 does not provide information on which target VEHICLE 0 visits *second*. However, the sparse nature of the matrix does indicate that a pattern of favorable route segments exists, with several notable ones persisting throughout the simulation. For example, segments 13-to-11, 11-to-12, 19-to-15, and 15–3 are present in the best solutions of all 21 replications. The matrix also provides marginal distribution information on potential destination targets j for any departure node i. For instance, the simulation suggests that whenever a UAV departs TARGET 3 its next stop will be TARGET 4 86% (18/21) of the time, or TARGET 5 the remaining 14%. Conversely, follow-on destinations after TARGET 36 are more uniformly split between TARGETS 35, 37, 38, 39, 45, and 48. Finally, we note that both the sparseness of the matrix and the distribution of its data intuitively make sense given the clustering of nodes into ROZs.

Our second analytical goal determines the utility of providing additional UAVs to the fleet. The routing frequency analysis suggests the current fleet of five UAVs are already underutilized (in none of the 21 replications were more than three UAVs used), while wind patterns, route length, and time windows remain the same. Therefore, since the hierarchical UAVP objective is to first maximize expected target coverage, then minimize total travel time, we increase the probability of additional loiter time as the most likely parameter to change in the Bosnia scenario. The service time itself (for those targets whose service times are randomly increased) is modeled as before using a uniform distribution on the range of individual service times given in Table 5. (The increased probability of having to stay at a given target for more than its minimum service time captures the operational condition of heightened activity in the areas under surveillance.) Specifically, for a given combination of vehicle availability and probability of loiter time (P_1), we conduct twenty replications and note which ones produce a feasible tour for its particular realization of the random variables Ps(i), ω_i, and τ_{ij}. For every combination of vehicle availability and P_1, we use the same random number streams; thus, by repeating the same twenty scenarios we can directly compare the results. Finally, we increase the number of tabu iterations for each replication to 1,000.

Table 7 shows the number of feasible solutions found out of twenty replications for each combination of loiter time probability P_l (rows) and available UAVs (columns). We first note that, for a given P_l, the number of feasible tours increases monotonically with respect to the number of available vehicles. Intuitively this stands to reason—each P_l represents a unique problem whose feasible solution space expands as one of its tight resource constraints is relaxed. However, the rate of increase differs considerably within each P_l problem scenario. For example, when $P_l = .5$ the marginal utility for the fourth UAV provides feasible tours in all twenty replications, whereas three UAVs limit the number of feasible solutions to just 35% of the time (7/20). Finally, comparing the marginal gains across the different problem scenarios shows that, for a given level of solution feasibility, a general pattern of increasing UAV requirements emerges as the probability of loitering increases.

Conversely, for a given number of available vehicles, we note in two instances a *nonmonotonically* decreasing number of feasible solutions as P_l increases. First, for two UAVs, as P_l increases from .1 to .3 to .5 the number of feasible solutions goes from 11 to 12 to 1, respectively. Second, for five available UAVs as P_l increases from .5 to .7 to 1.0 the number of feasible solutions are 20, 19, and 20, respec-

Table 6. Bosnia Scenario—Replication #16 (Hours)

		Input Parameters		*Simulation Results*				*Input Parameters*	
Type	**Node ID**	**Early Arrival**	**Late Arrival**	**Arrival**	**Depart**	**Wait**	**Service Time**	**Min Service**	**Max Service**
				First Vehicle/Tour					
Depot	0	9.25	23.75	9.25	9.25	0.00	0.000	0.000	0.00
Node	20	10.25	15.00	9.72	10.25	0.53	0.033	0.033	2.00
Node	14	10.25	15.00	12.29	12.29	0.00	0.033	0.033	0.50
Node	17	10.25	15.00	12.34	12.34	0.00	0.167	0.033	0.50
Node	18	10.25	15.00	12.43	12.43	0.00	0.033	0.033	0.50
Node	19	10.25	15.00	12.64	12.64	0.00	0.033	0.033	0.50
Node	15	10.25	15.00	12.68	12.68	0.00	0.033	0.033	0.50
Node	3	10.25	15.00	12.72	12.72	0.00	0.033	0.033	0.25
Node	4	10.25	15.00	12.76	12.76	0.00	0.033	0.033	0.50
Node	5	10.25	15.00	12.79	12.79	0.00	0.033	0.033	0.50
Node	8	10.25	15.00	12.84	12.84	0.00	0.033	0.033	0.50
Node	7	10.25	15.00	12.87	12.87	0.00	0.033	0.033	0.50
Node	6	10.25	15.00	12.91	12.91	0.00	0.033	0.033	0.50
Node	9	10.25	15.00	12.95	12.95	0.00	0.033	0.033	0.50
Node	10	10.25	15.00	12.98	12.98	0.00	0.489	0.033	0.50
Node	2	10.25	15.00	13.47	13.47	0.00	0.500	0.500	3.00
Node	13	10.25	15.00	14.02	14.02	0.00	0.033	0.033	0.50
Node	11	10.25	15.00	14.12	14.12	0.00	0.033	0.033	0.50
Node	12	10.25	15.00	14.22	14.22	0.00	0.033	0.033	0.50
Node	21	10.25	15.00	14.38	14.38	0.00	0.033	0.033	1.00
Node	16	10.25	15.00	14.47	14.47	0.00	0.033	0.033	0.50
Node	1	10.25	15.00	14.52	14.52	0.00	0.500	0.500	3.00
Node	32	19.00	23.00	15.02	19.00	3.98	2.992	0.500	3.00
Node	51	19.00	23.00	22.03	22.03	0.00	1.704	0.500	2.00
				Second Vehicle/Tour					
Vehicle	53	9.25	23.75	24.21	9.25	0.00	0.000	0.000	0.00
Node	26	15.00	17.25	9.64	15.00	5.36	0.033	0.033	0.50
Node	28	15.00	17.25	15.04	15.04	0.00	0.033	0.033	0.50
Node	27	15.00	17.25	15.08	15.08	0.00	0.114	0.033	0.50
Node	25	15.00	17.25	15.27	15.27	0.00	0.407	0.033	0.50
Node	24	15.00	17.25	15.69	15.69	0.00	0.083	0.083	2.00
Node	23	15.00	17.25	15.81	15.81	0.00	0.666	0.083	2.00
Node	22	15.00	17.25	16.51	16.51	0.00	0.083	0.083	2.00
Node	31	17.50	18.50	16.85	17.50	0.65	0.333	0.333	0.67
Node	30	17.50	18.50	17.84	17.84	0.00	0.625	0.333	0.67
Node	29	17.50	18.50	18.48	18.48	0.00	0.333	0.333	0.67
Node	52	19.00	23.00	19.16	19.16	0.00	0.085	0.033	1.00
Node	43	19.00	23.00	19.37	19.37	0.00	0.398	0.033	0.50
Node	42	19.00	23.00	19.84	19.84	0.00	0.033	0.033	0.50
Node	44	19.00	23.00	19.95	19.95	0.00	0.033	0.033	0.50
Node	33	19.00	23.00	20.02	20.02	0.00	0.500	0.500	3.00
Node	35	19.00	23.00	20.52	20.52	0.00	0.118	0.033	0.50
Node	34	19.00	23.00	20.65	20.65	0.00	0.033	0.033	0.25
Node	46	19.00	23.00	20.69	20.69	0.00	0.064	0.033	0.50
Node	50	19.00	23.00	20.75	20.75	0.00	0.033	0.033	0.50
Node	36	19.00	23.00	20.80	20.80	0.00	0.033	0.033	0.50
Node	37	19.00	23.00	20.83	20.83	0.00	0.033	0.033	0.50
Node	41	19.00	23.00	20.87	20.87	0.00	0.033	0.033	0.50
Node	40	19.00	23.00	20.91	20.91	0.00	0.033	0.033	0.50
Node	38	19.00	23.00	20.94	20.94	0.00	0.363	0.033	0.50
Node	39	19.00	23.00	21.31	21.31	0.00	0.455	0.033	0.50
Node	49	19.00	23.00	21.82	21.82	0.00	0.033	0.033	0.50
Node	45	19.00	23.00	21.92	21.92	0.00	0.033	0.033	0.50
Node	48	19.00	23.00	21.97	21.97	0.00	0.235	0.033	0.50
Node	47	19.00	23.00	22.22	22.22	0.00	0.033	0.033	0.50
Depot	54	9.25	23.75	22.77	9.25	0.00	0.000	0.033	0.00

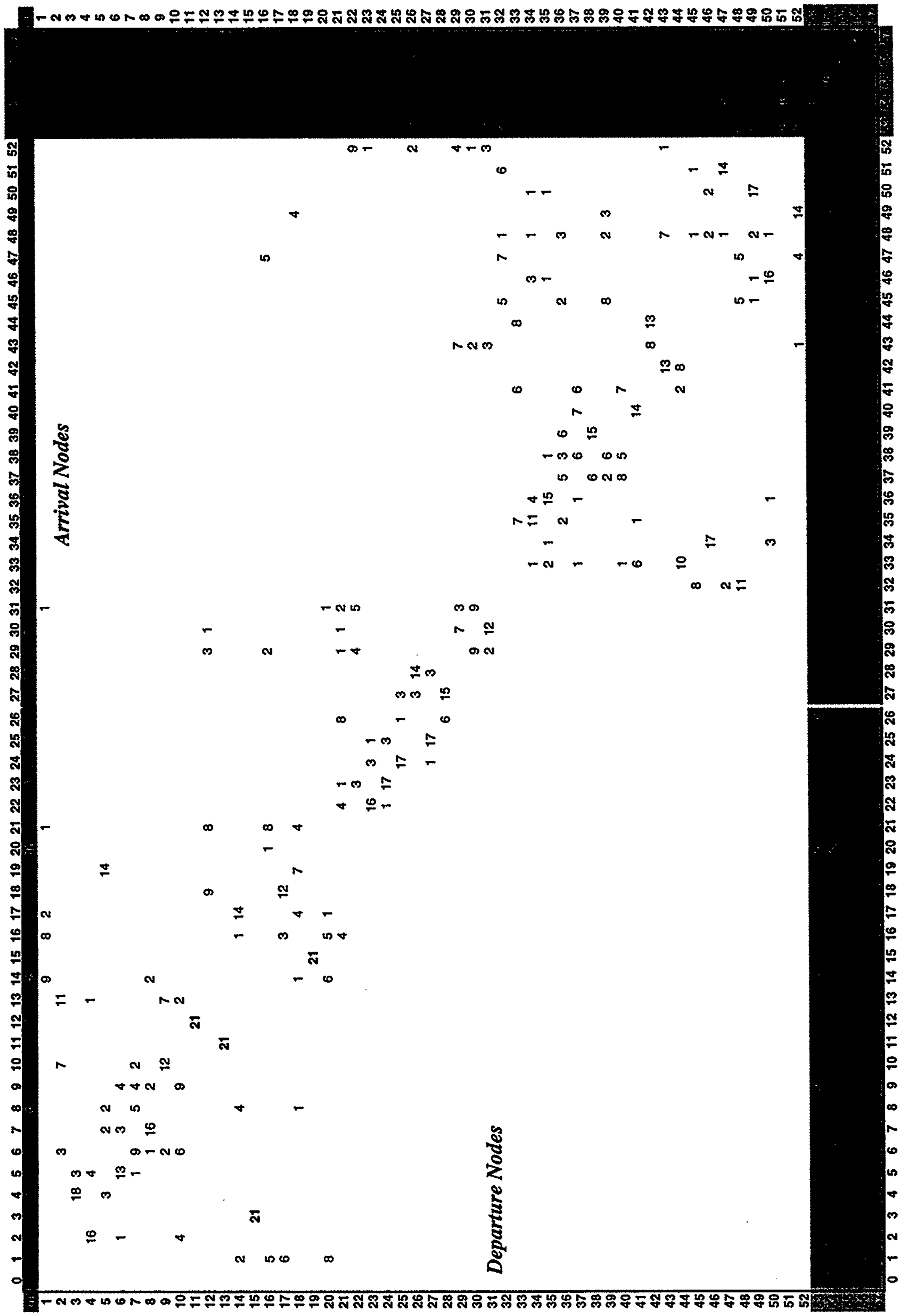

Figure 7. Bosnia Scenario Route Frequency.

Table 7. No. of Feasible Tours in 20 Replications of Bosnia Scenario.
(P_l = probability of loitering)

P_l	# of Available UAVs				
	1	2	3	4	5
0.1	7	11	20	20	20
0.3	0	12	13	20	20
0.5	0	1	7	20	20
0.7	0	0	5	17	19
1.0	0	0	0	0	20

tively. Although the general column pattern is intuitively appealing—for a fixed number of UAVs, as loiter time increases the number of observed feasible solutions decreases—monotonicity will not necessarily hold in all cases. This occurs since, unlike changing UAV availability for a constant P_l, changing P_l for a constant number of vehicles implies a unique problem that presents a fundamentally different solution space to the tabu search.

CONCLUSIONS

This paper applies reactive tabu search to unmanned aerial vehicle routing problems using Monte Carlo simulations that incorporate the stochastic nature of real-world UAV scenarios. Embedding RTS objects that use proven heuristic methods within a simulation provides near-optimal solutions to individual realizations of the target environment, which in turn can form the basis for identifying routing assignments that are robust to variations in wind, loiter times, and probability of survival. Additionally, the work described here can be applied towards evaluating the military worth of new and innovative concepts that attempt to improve UAV mission performance, and assess the marginal utility of additional UAVs.

Finally, our research also contributes to the practical application of RTS with the creation of the MODSIM libraries. Future code can be quickly tailored to specific members of the GVRP family by using these libraries. Even if the programmer is not using MODSIM, the libraries provide a straightforward translation given the "strongly typed" nature of MODSIM and the strict adherence to code encapsulation they embody. Their use can reduce the up-front coding time so often required in GVRP research.

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An Historical Perspective on Operations Research in the United States Air Force

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ABSTRACT

In 1955, LeRoy A. Brothers served as the fourth President of the Operations Research Society of America. At the time, he was Chief of the Operations Analysis Division, in the Directorate of Operations, Office of the Air Force Deputy Chief of Staff for Operations. The following paper is a scanned version of an in-office manuscript prepared by Dr. Brothers in September 1952, which he had entitled, "Operations Analysis in the US Air Force: A Brief Description Addressed to the Air Force Officer." Portions of the original paper were extracted and edited for a refereed article published in February 1954, in Volume 2 of the *Journal of the Operations Research Society of America*, with the title "Operations Analysis in the United States Air Force." Though there is major overlap between the *JORSA* article and the 1952 report, the original report was much more directed at line military analysts (note the difference in the two titles!) than the more general paper published by ORSA. We believe, therefore, that Dr. Brothers' original words are especially germane for today's community of practicing military operations research analysts.

Roy Brothers' formal career in OR only spanned the short period 1943–1958, taking him from a World War II involvement in operations analysis dealing with targets and weapons for the war in the Far East and the U.S. Strategic Bombing Survey operations in Japan, to his civilian time as coordinator of strategic, tactical and defense studies at Air Force Headquarters in Washington, D.C. Before the war, Dr. Brothers had been on the civil engineering faculty at the Drexel Institute of Technology in Philadelphia, where he returned in Fall 1958, as Dean of the School of Science and Engineering. In the years following his return to Drexel, he served as Vice-President for Academic Affairs and Provost, but never resumed his involvement in formal OR before his academic retirement. However, his contributions to OR were significant. Throughout his time with the Air Force, he showed outstanding insights regarding the role of quantitative methods in national defense decision making, and was an exemplary leader of the kinds of interdisciplinary teams of civilian and career staff so necessary for military problem solving. His 1955 presidency of ORSA was marked by special foci on understanding the major ingredients of successful OR project work and the development of appropriate paradigms for OR education. Dr. Brothers passed away in 1985.

In reading this work, please note that we have made absolutely no changes in textual content whatsoever. The consistent reference to the male gender throughout the paper was, of course, the standard style of the times.

The editors wish to express their special thanks to Professor Clifford W. Marshall of the Polytechnic University, New York, for his help in locating a copy of the original paper authored by Dr. Brothers in 1952.

Operations Analysis in the US Air Force: A Brief Description Addressed to the Air Force Officer (September 1952)

by

LeRoy A. Brothers
Chief of the Operations Analysis Division Directorate of Operations Office of the Air Force Deputy Chief of Staff for Operations

Military OR Heritage Article

A. Scope of This Paper. Operations Analysis in the U.S. Air Force makes scientific studies of operations in order to furnish commanders and staffs with quantitative bases for decisions. The purpose of this discussion is to give the Air Force officer an understanding of this scientific tool so that he may make full use of it. The conditions necessary for successful use of operations analysis will be discussed, also what it can do and what it should not be expected to do; examples of successful operations analyses will be described.

B. Origin and Development of Operations Analysis. Just prior to World War II the British armed forces received a new and promising component for the air defense system—radar. There was not time to progress through the established procedure of service testing, operational suitability testing, modification, and training to development of adequate doctrine and fully operational equipment. As an experiment a civilian scientist who had played a prominent part in the development of radar was given a corresponding responsibility to work jointly with the military people in solving the many operational problems that arose in adapting radar for early warning and for ground controlled interception. The experiment was highly successful and the British forces quickly developed the use of civilian scientists to assist in the solution of problems of operations. They designated the activity operational research. Operational research sections soon were attached to the staffs of RAF Bomber Command, Fighter Command and Coastal Command, and of commands of the other services; later the activity was expanded to include overseas commands.

Following our entry into the war both the U.S. Navy and Air Force were quick to follow the British lead. Each departed from tradition and brought in groups of civilian specialists and assigned them to military staffs in wartime in combat zones. The first operations analysis section, as it came to be known in the Air Force, went to VIII Bomber Command Headquarters in September, 1942. As they arrived they were greeted by the Commanding General with the question, "How can I put twice as many bombs on my targets?" From that day to this Operations Analysis has received questions of that scope and difficulty, and has dealt with them successfully.

Operations Analysis grew rapidly during World War II; between the fall of 1942 and VJ-Day there were a total of 26 operations analysis sections established at Air Force headquarters, including every combat air force and a number of ZI headquarters. The size of sections varied considerably but the average was about ten analysts. An effort was made to have a wide variety of scientific skills in each section and to tailor each section to the needs of its command. At each headquarters the analysts worked on the problems of their own command, generally upon the request of the commander, his staff agencies, or the commanders of subordinate units of the command.

Toward the end of World War II the Chief of Staff asked all the commanders who had used operations analysis whether it should be continued in the postwar Air Force and whether it should be civilian. The answers were a unanimous yes, it should be continued and, with a single dissent, that it should be civilian.

Operations Analysis suffered the same rapid disintegration at the end of the war as the rest of the military establishment. In January 1946 there were about a dozen operations analysts left in the Air Force and several of them were finishing up wartime work. From this small nucleus however there has been a slow, healthy growth, based upon demonstrated postwar usefulness rather than upon World War II reputation. In spite of a somewhat accelerated growth since the fighting began in Korea the organization is still quite small as may be seen in the accompanying chart showing the organization as of September 1952 (see Appendix).

The USAF is not alone in continuing this activity since World War II. The British forces have continued it and continue to call it operational research. The activity also continues in the armed forces of Canada and Australia. In this country the Navy has continued it and calls it operations evaluation. The U.S. Army did not have such an activity dur-

ing the war but now has its Operations Research Office. The Joint Chiefs of Staff now have their own organization called the Weapons Systems Evaluation Group. There is now much interest in England and in this country in applying operations research to industrial problems and to problems of government agencies other than the military agencies. In May 1952, a group of scientists from industry, government, and universities met and founded the Operations Research Society of America. This new professional society has as its purpose: "The advancement of the science of operations research, through exchange of information, the establishment and maintenance of professional standards of competence for work known as operations research, the improvement of the methods and techniques of operations research, and the encouragement and development of students of operations research."

C. Definition of Operations Analysis. Operations analysis is an organization, as has been seen above, and it is a philosophy or method of attacking problems. Although no brief definition of operations analysis is very satisfactory, the first sentence of this paper does attempt one. The official definition is given in Air Force Regulation 20-7 which established the postwar organization. A copy of AFR 20-7 (revised 5 July 1949) is attached. The following discussion is intended to define operations analysis. It will be presented in two parts: (a) conditions under which operations analysis is likely to be successful, and (b) characteristics of operations analysis.

(a) *The following conditions are necessary for the success of operations analysis:*

(1) Real problems must exist. Operations analysis is not research for the sake of research. Nor is it research for the sole purpose of extending the frontiers of knowledge. The importance of such research is unquestioned, and it is an interesting and satisfying activity for the scientist. But it is not operations analysis. Operations analysis is research for the purpose of solving operational problems. If there are not real and existing problems there is no need for operations analysis.

(2) The problems must be such that the commander can do something about them once solutions are found. A commander is sometimes faced with problems caused by things completely beyond his control. Barely, if ever, should his analysts work on such problems. Solutions produced by the analysts should furnish their commander a guide to action he can take.

(3) It is necessary that operations analysts have access to all information relevant to their work. Since the analysts generally work on problems of very wide scope it is usually necessary for them to have access to all intelligence both external and internal. The chief of the operations analysis office should attend staff meetings, commanders' meetings, and the like.

(4) The analysts must have freedom to do unhurried, unbiased research. Scientists do not do good research at the feverish pitch at which staff officers generally work. While operations analysts can and do help on "crash" problems, in the interest of getting the most from their scientific training drawing them into this kind of activity should be held to a minimum.

(5) The analysts must have freedom to draw conclusions from their research and to present recommendations based on their conclusions just as they draw them. Operations analyses should be uncolored by current policy, the commander's opinion, and other such factors. The analysts' job is to do objective, factual research; they have no responsibility for operations, for normal staff work, nor for making decisions; theirs is an advisory responsibility only. The commander weighs the analysts' recommendations in the

light of his own experience and judgment, current policy, and all other pertinent factors in determining his course of action.

(6) The last and perhaps most important condition necessary for the success of operations analysis is the opportunity to present recommendations at a level at which effective action, if justified, can be taken. This means that the chief of the operations analysis office should report high on the staff, preferably to the commander through the vice commander. Experience has shown that where operations analysis is placed low on the staff it works on problems of lesser scope, tending toward the area of responsibility of the staff agency to which it is attached; other staff agencies and subordinate commanders find it increasingly difficult to obtain assistance from analysts; even the commander gets less benefit from his operations analysis office when it is attached low on the staff. The most serious danger, and a very real one, is that conclusions of operations analyses may be suppressed if they are not in accord with the opinion of the staff officer through whom the operations analysis office reports, or with his idea of the commander's opinion or policy.

(b) *The following are among the outstanding characteristics of operations analysis:*

(1) Operations analysis is the study of going operations, without interrupting the operations. War will not wait while the scientist thinks. The bombardment operation, the transport operation, the training operation, the planning operation, the development or the procurement operation—any or all may be studied by the analyst as the operation goes on. Operations, as here used, is defined very broadly. Operations analysis studies may be concerned, literally, with combat operations in progress; or they may be concerned with planning, with the establishment of requirements, with organization or procedures for training or maintenance, with cost and effectiveness of weapons, equipments, or tactics for current or future operations. Where real problems exist, regardless of subject matter or which staff agency is responsible for their solution, operations analysis may be called on for assistance.

(2) The primary purpose of operations analysis studies is to improve the operations under study—to reduce bombing error, to improve weapon selection, to devise more effective tactics, to reduce attrition. There are two major by-products of operations analysis studies, which sometimes become primary purposes. One of these is the discovery of needs for new or modified weapons, equipment, or tactics. It is inevitable that studies of operations will discover such needs, needs which the requirements staff agency can translate into military requirements. The second major by-product is the production of planning factors. Quantitative measures of results of recent operations furnish the most accurate guide to probable results of operations in the immediate future, if conditions surrounding the operations are not expected to change. If the operation being planned is for the distant future past experience is a less reliable but still useful guide, and the analyst has a more difficult job.

(3) Operations analyses are scientific studies made by scientists, and thus differ from normal staff studies. Preferably they should be quantitative studies based upon accurate data recording reliable measurements. When it is necessary to rely upon qualitative information, in whole or in part, sound scientific principles still may be applied and useful results be obtained.

(4) Operations analysis is team research. A team of analysts is assigned to a problem, the analysts being selected so as to bring to bear on the problem the scientific skills judged most applicable to its solution. Often it is possible to have one or more officers on the team also (usually the officers whose problem is being studied), thus bringing together the operational experience and military judgment of the officer and the scientific knowledge and experience of the analyst. Under any circumstances it is essential for analyst and officer to work closely together, to assure that the problem as formulated for solution by the scientist is, in fact, the real problem with which the officer is faced. Assumptions upon which the study will be based should be worked out jointly by the officer and the analyst.

(5) The ideal operations analysis begins with the selection of operational parameters to be measured and the gathering of reliable data. Then follows a rigorous analysis of the data. From the analysis a plausible theory is formulated relating cause and effect. The next step is the testing of the theory, preferably using new data. If new data are not available the original data or parts of it can be used, together with a variety of theoretical tests. Once the theory is tested and proved it is used for predicting purposes. Often it is not possible to achieve this ideal, but there have been many cases where the problem has been handled in this exact manner.

(6) The final results of operations analyses are recommendations for action. Here the commander is given recommendations based upon quantitative analysis. The commander and the analyst are fully aware that a decision does not follow automatically from the result of a scientific study. However it furnishes the commander a firm foundation upon which to base his decision, considering in addition the many other factors affecting a decision, e.g., budgetary and political matters.

D. Organizational and Functional Relationships. From what has gone before it is clear that Operations Analysis consists of groups of scientists attached to Air Force staffs, that they make scientific studies of the problems of their own commands in order to provide quantitative bases for decisions, and that they work for the commander and the officers responsible for operations, requirements, and plans. Air staff agency or subordinate commander may request the assistance of operations analysis. Within the capability limitations of the operations analysis office assistance will be given. Priorities among requests are established by the commander with the advice of the chief of the operations analysis office.

After an operations analysis office becomes a fully established part of its headquarters it develops a continuing program of research which will keep it prepared to assist its command in solving its problems. Not infrequently, under such circumstances, the operations analysis office is able to anticipate problems and to help its command prevent their arising.

An obvious factor limiting the capability of the operations analysis office is the number of analysts assigned. Another limiting factor is the number of scientific skills represented among the assigned analysts. It has been found desirable to have a broad coverage of the sciences, not limited to the physical sciences only. The fields of science represented on the staff of the Headquarters, USAF Operations Analysis Division in 1952 were mathematics, statistics (mathematical and experimental), physics (nuclear, general and electronics), aerodynamics, engineering (structural mechanical, industrial, aeronautical and electrical), education, psychology, biology, medicine and economics. The smaller offices necessarily have a less broad coverage of the sciences.

The desirability of placing operations analysis high on the staff has been pointed

out. This will assure the availability of operations analysis to all parts of the staff and command, will assure that each problem is considered in its relationship to the broad mission of the command, and will help prevent the use of the analysts on normal staff work. The last point is an important one. It is inefficient to use operations analysts on normal staff work. It prevents them from carrying out their real function of scientific study of command problems. The trained, and experienced officer is much better at staff work than the analyst.

An operations analysis office in a command belongs to its own commander. He is authorized to establish an operations analysis office if he wants one; he is not required to do so. He pays for his analysts from his own personnel ceiling and from his own budget. His analysts work on his problems and report to him. Their work is not directed from Headquarters, USAF, nor do they report to Headquarters, USAF. The Operations Analysis Division in Headquarters, USAF has the responsibility of helping the commands determine their requirements for operations analysts; of selecting, indoctrinating and recommending appointment of all operations analysts in the USAF; and of maintaining technical liaison with established offices in the commands and with research and development laboratories and projects. The Headquarters Division gives considerable assistance to new offices just after they are established, generally by sending one or more experienced analysts to the command to introduce the new analysts, to help them get set up for business, to help them select their first problems and get their first studies started. The technical liaison function is more important for the overseas offices than for those in the ZI. Operational guidance is furnished research agencies on an informal basis, and through these contacts information regarding new developments of interest and value to Air Force commands is obtained. This activity is carried on by all operations analysts, most freely, of course, by those assigned to ZI commands.

In addition to the responsibilities detailed above the Operations Analysis Division of Headquarters, USAF does scientific studies of Air Staff problems just as any other operations analysis office works for its commander and his staff. Administratively the Headquarters office is a division of the Directorate of Operations but it does studies for the Secretary of the Air Force, the Chief of Staff, and any Air Staff agency requesting assistance, within its capability.

Reports, information, and visits are exchanged among all operations analysis offices. Occasionally studies are done jointly by two or more offices. Technical conferences are held at intervals of three or four months at which technical papers are presented and discussed. The topic is usually one on which a number of offices are working, and all operations analysis offices are invited to send representatives. From these conferences accrue all of the usual benefits of scientific meetings.

Such Air Force research contractors as RAND and the Institute of Air Weapons Research must necessarily do some operations analysis themselves. However their primary purpose is to advise the Air Force on the distribution of its research and development funds whereas Operations Analysis is primarily interested in improving operations. This statement is a considerable oversimplification yet serves to indicate the essential distinction between the two types of organization. There is an excellent spirit of cooperation between Operations Analysis and such agencies, with no undesirable duplication of interest or work. Informal contact is maintained also with the other operations analysis organizations in the Department of Defense and in Canada and England.

E. Examples of Operations Analysis Studies. An examination of a few examples of operations analysis studies is perhaps the best way to achieve an appreciation of the kinds of things to expect of analysts. Examples from World War II will be presented first, followed by some from the postwar work.

(a) *Examples from World War II.*

(1) Bombing Accuracy. Early in this paper it was stated that the first ques-

tion addressed to the first Air Force operations analysts by the Commanding General of the VIII Bomber Command was, "How can I put twice as many bombs on my targets?" It is interesting to note that the general did not ask, "How can the training of bombardiers be improved?" or "How can the best lead bombardiers be selected?" or "How can errors in target recognition be reduced or eliminated?" or "How can errors in the use of the bomb sight be reduced or eliminated?" The general did not have the departmental point of view represented by any of these alternative questions. He quite typically and properly took the position that placing bombs on the target was the end result of a long and complex operation. He had the responsibility to carry out an assigned mission of strategic bombing. He wanted to know how to carry out his assignment efficiently. If it had been evident that the difficulties that plagued his command at the time were deficiencies in training or unsuitable tactics or inadequate prestrike indoctrination of aircrews there were appropriate sections of his staff to which he properly could have referred his problem. As a matter of fact, all sections of his staff were already working on the problem, each on its own phase. The cause of the difficulties was not evident at the time. It might have been any one of those named; it might have been all or them; it might have been one or more factors which had gone unrecognized. The general wanted a diagnosis of the sources of difficulty present in the whole system of operations for which he was responsible; he wanted a basis for effective action he and his subordinate commanders could take.

The analyst's first action was to study the bombardment mission until they understood thoroughly how it was carried out—a few of them actually flew a few missions. Then they devised a mathematical model of the mission—an expression in which mathematical symbols were used to represent the factors affecting the success of the mission and which stated possible relationships among the factors and between them and the payoff factor, the factor representing the measure of effectiveness of the mission. The next step was to devise accurate means of measuring, recording, and reporting the factors. At this point a lot of hard thinking was necessary, by analysts and officers, to select the most important of the many factors, in order to keep the mathematics manageable and meaningful.

A major product of this hard-thinking was the decision that operations analysts working for a combat command should not devote much effort to perfecting an all-inclusive model of the operation. It was decided to divide the operation into parts that might be studied more or less independently. The discussion that follows is concerned with the intensive study that was made of that part of the bombardment operation during which the bombs are aimed and released. Even in this small but crucial part of the operation it was found that it often paid to keep the theory simple and the mathematics to a minimum.

As the actual bomb aiming-releasing part of the operation was studied particular attention was given to the payoff factor, the measure of effectiveness. A payoff factor involving such things as target size, shape, and character was considered and discarded. Finally it was decided to use as the measure of effectiveness the per cent of bombs falling within some arbitrary distance measured from the assigned aiming

point (AP).[1] Actually, the distance chosen was 1000 ft, as bombing improved 500 ft was used.

Thus a theory was postulated, in this case, actually, before analysis of data, since existing data were too meager for effective analysis. As data became available they were used immediately to test and modify the theory, dropping factors, adding others, changing relationships, etc., until the mathematical model did, in fact, represent with sufficient accuracy this part of the bombardment mission, as it was carried out at that time under the then existing conditions. A prime factor to be tested was the payoff factor—was it true that as the per cent of bombs falling within a fixed distance of the assigned AP increased the number of bombs falling in target areas increased, and target damage increased? It is a matter of record that the answer was in the affirmative.

As the analysis began there was no reliable source from which the chosen measure of effectiveness could be obtained. Post-attack photos of the target were unsatisfactory, as they recorded only the bombs falling near the target (not all of them could be distinguished) and, further, furnished no means of identifying the bombs found with the formations which dropped them. The analysts suggested that each formation obtain a series of photographs on the bomb run, using cameras carried by the bombardment aircraft themselves, showing their bombs from positions just beneath the aircraft until they hit the ground (these photographs came to be known as "strike photos" or "strike attack photos"). This would require each formation to fly straight and level over the target until its bombs hit the ground, and probably would increase our losses and battle damage at the targets. Would the information gained pay? Would it furnish a basis for later improvements which would reduce losses enough to offset the immediate increased cost? Courageous commanders decided to take the calculated risk—the analysts obtained adequate data, the way was shown to very great improvements, the net gain was tremendous.

It proved to be very difficult to separate the effects of some factors known or suspected to affect bombing error. For example, when the enemy increased his anti-aircraft gun defense at the targets missions were flown at higher altitudes and bomb runs were made downwind. Analysis in the theater failed to separate effects of guns and altitude, but did establish the relationship between bombing error and these two factors taken together. Effect of ground speed seemed to be negligible. Postwar analysis of selected samples of homogeneous data from Eighth Air Force operations separated guns and altitude and placed them in that order as regards effect on bombing error; again, effect of ground speed appeared negligible, though it should be noted that differences in ground speeds were relatively small. Inadequacy of data prevented a determination of the effect on bombing error of enemy fighter attacks.

On the other hand it was possible to show clearly the effects of certain factors, such as the number of independent aimings per formation, in-

[1] The Eighth Air Force was attacking in formations in order to provide mass fire power against German fighters. All aircraft in a formation attempted to release their bombs simultaneously, resulting in the bombs from a formation striking the ground in a pattern. The term "aiming point," as used here, refers to the point on the ground at which it was desired for the center of the pattern to strike, generally the center of the target area. This usually was not the actual point at which the bombardier sighted.

tervalometer setting, and size of formation. In addition to the per cent of bombs falling within a stated distance of the assigned AP the analysts measured the size of bomb pattern and the aiming error of bomb pattern from each formation. The bomb pattern was defined as the rectangle on the ground obtained by drawing two straight lines parallel to the track of the formation containing between them 80% of the bombs and two lines perpendicular to the track containing 80% of the bombs. The aiming error was defined as the distance from the center of this rectangle to the assigned AP. The circular probable error (CEP) of pattern centers was defined as the radius of a circle centered on the assigned AP containing one-half the pattern centers. The following history of the Eighth Air Force will be interesting.

In 1942 patterns were much too long to achieve appreciable damage to targets and data were inadequate for precise description of the bombing.

By 1943 adequate data were being gathered and reported, but patterns were both too long and too wide. CEP of pattern centers was over 1,000 feet. Percentage of bombs within 1,000 feet of assigned AP was approximately 15. All bombardiers were sighting for range with only the lead bombardier sighting for deflection.

The analysts theorized that bombing would be improved if only the lead bombardier sighted and the wing bombardiers dropped their bombs when they saw the bombs fall from the lead airplane. Commanders tried this with the following results. Pattern length was decreased approximately 30%; pattern width was decreased approximately 4%; CEP of pattern centers was decreased approximately 4%; per cent of bombs within 1,000 feet of assigned AP increased to approximately 25. Relatively long intervalometer settings were being used.

Analysts theorized that minimum intervalometer or salvo release would improve the bombing. Some commanders tried one, some the other. Results: pattern length decreased an additional 20%; pattern width decreased an additional 12%; CEP of pattern centers decreased an additional 27%; per cent of bombs within 1,000 feet of assigned AP increased to approximately 37. This was for the period from October, 1943, to March, 1944.

When all formations used salvo release, the results were: pattern length decreased an additional 35%; pattern width decreased an additional 23%; CEP of pattern centers decreased an additional 10%; per cent of bombs within 1,000 feet of assigned AP increased to approximately 66.

All of the above figures are for formations of from 18 to 21 aircraft. Analysts suggested that smaller formations might produce better bombing. Twelve to 14 aircraft formations were tried with the following relatively small improvement: pattern dimensions unchanged; CEP of pattern centers decreased an additional 19%; per cent of bombs within 1,000 feet of assigned AP increased to approximately 68. This was for the period from late 1944 through early 1945.

The overall increase of bombs within 1,000 feet of assigned AP from 1942 to 1945 was well over 300%. Since the assigned AP usually was the center of the target area, this practically is equivalent to at least a 300% increase in bombs in the target area.

Many other suggestions were made by the analysts and many modifications of tactics were tried by commanders earnestly seeking to

improve the operation. Some resulted in improvements, others did not. On one occasion the analysts pointed out to the Commanders that excessive pattern width was not properly chargeable to the bombardier but likely was due to ragged flying. Promptly the commanders called the pilots in for lectures. As a result pattern widths were reduced.

The study just described was continued over several years and produced major results. Concurrently many other studies were carried out by Eighth Air Force analysts. The following is a sampling of them. They studied cause and effect related to ditchings in the channel. Gasoline consumption studies led to modified cruise control and reduction in the rate of ditchings. Battle damage studies led to the requirement for armament in the nose of the bomber and to modifications in defensive formations and tactics. Weapons effectiveness studies led to better bomb-fuze selections.

(2) Flexible Gunnery. During the North African campaign the IX Bomber Command was suffering heavy bomber losses in air combat with German fighters. The defensive fire from The bomber's hand-held flexible guns was ineffective against the German fighters who became progressively aggressive. The problem was turned over to the operations analysts who made a theoretical study of the relative motion of bomber-fighter-projectile, a complex but not difficult task. The instructions given the gunners during training were compared with the mathematical model; they were found to be correct but extremely complex. Discussions with gunners revealed that due largely to the complexity of the aiming rules the gunners had abandoned them and fallen back on common sense based on personal experience in duck shooting where it is necessary to lead the target. This turned out to be exactly wrong, due to the motion of the gun platform, i.e., the bomber. So the analysts devised a new set of simple aiming rules which, when put into use quickly caused the Germans to gain respect for our gunners. The new rules soon appeared in gunnery manuals used by the Air Force, the Navy, and the Marines.

(3) Low Altitude Radar Bombing of Japanese Shipping. Analysts in the Thirteenth Air Force in the South Pacific studied the early use of a radar bombing equipment known as LAB in night bombing of Japanese shipping. These studies which derived optimum altitude, angle of approach, intervalometer setting, and number of passes per attack were distributed in report form to all other operations analysis sections. The reports also included data on sorties per month, tonnage of enemy shipping sunk, etc.

Analysts in the Fourteenth Air Force, in South China in early 1944, based on the Thirteenth Air Force experience, predicted that the Fourteenth Air Force B-24's, if equipped with LAB, could sink 900 tons per sortie of Japanese shipping in the Formosa Straits (Thirteenth Air Force had sunk about 300 tons per sortie—difference due to relative densities of Japanese traffic). The analysts pointed out that a sustained campaign at this rate would prove so costly to the Japanese that they might be forced to overrun the Fourteenth Air Force bases in China.

The calculated risk was taken, after two-and-one-half months of LAB operations the Fourteenth Air Force had sunk an average of 800 tons per sortie, by the fall of 1944 the Japanese had driven the Fourteenth Air Force out of all its East China bases.

(4) Ship-Length Computer. XX Bomber Command B-29's flying over Japan

from bases in China in 1944 often sighted Japanese Naval ships. There was much concern at that time over the whereabouts of the Japanese fleet—what was left of it. The B-29 ship sightings were a fine potential source of intelligence. But it was difficult for crew members to judge a ship's dimensions and hence its type from the altitudes at which the B-29's operated.

An operations analyst devised a simple computer for use with the bombsight which would determine accurately the lengths of ships. The computer was easily made from scrap aluminum from crashed aircraft. The analyst flew on the first experimental mission to try out the computer and had the incredible good fortune to sight and identify the main Japanese fleet in the Inland Sea. This intelligence was relayed to the Navy and paved the way for the battle in which the Japanese fleet was annihilated.

(5) Cruise Control. Analysts in the Twentieth Air Force studied the cruise control procedures of the B-29's attacking the Japanese home islands from the Marianas in late 1944 and 1945. In the earliest missions from Guam to Japan the B-29's carried two to three tons of bombs. The work of the analysts together with the courage and determination of the flight engineering officers steadily increased this to a figure of seven to eight tons toward the end of the war. An analyst flew as flight engineer on a test flight of a B-29 from Guam on which 19,600 pounds of bombs were dropped on Tokyo to demonstrate his proposed cruise control procedures.

(b) *Postwar Examples.*

(1) Attrition Studies. Much of the work of the postwar operations analysts, particularly in the commands, has been similar to that just described. The Air Force has continued to carry out operations; training operations, test operations, and, in Korea, combat operations. Studies of these operations made by operations analysts have resulted in improvements in the operations. First, however, a different type of study will be described—the attrition study. Since mid-1946 Operations Analysis has been estimating combat attrition for war plans, and has worked assiduously to devise increasingly reliable methods of making such estimates. This example is chosen because it will demonstrate rather graphically the increased difficulty of the analyst's job in cold war as compared to his job in hot war.

The war planner's product must be quantitative to be meaningful; among his jobs is to determine what force is required to achieve the aims of a war plan, or to determine what can be achieved with certain forces. The first is a requirements study, the second a capabilities study. Logically, the war planners turned to Operations Analysis in 1946 for assistance in extrapolating from World War II to hypothetical wars at times and under conditions assumed not far removed from World War II. Operations Analysis possessed both data and experience which proved of great value. As years passed the problem increased in difficulty due to the decreasing applicability of World War II combat data and the increasing performance and complexity of weapons systems. This has placed a greater burden on the analyst and has forced him to use theories which have not been subjected to the acid test of combat experience. It has also placed a greater premium on effective cooperative work of analyst and officer to assure the highest degree of reliability of war planning factors.

The first question the war planners asked the analysts in 1946 was,

approximately, "What could we accomplish with a certain number of groups of certain types of aircraft if we were attacked by a certain enemy nation at a specified time?" The analysts pointed out at once that to produce a comparatively reliable answer to the question would require the joint effort of people from Intelligence, Operations, War Plans, and Operations Analysis. Such a team was put together and work was begun.

The first step was to visualize the most probable course of events in the hypothetical war, then to subject this to critical scrutiny. An attempt was made to visualize how the most probable course would change if alternative events occurred at all likely points. The next step was to develop a mathematical model for the campaign. As in the examples above, the model was made as simple as was consistent with the campaign as visualized, symbols being used for essential factors, all others being eliminated. The determination of the essential factors was in itself a difficult and important part of the analysis. In the process of developing and testing the model data from World War II campaigns were used. The model was considered satisfactory when it would predict with reasonable reliability the results known to have been achieved in World War II. In other words, the model would predict, with reasonable precision, the damage actually done to World War II target systems when the actual figures were used (from World War II campaigns) for forces dispatched, aborts, losses to enemy aircraft and ground fire, operational losses, unknown losses, navigational errors, gross errors, bombing accuracy, malfunctions, and other factors.

Once a satisfactory model was available it was used in analyzing the hypothetical campaign. Great care was exercised that the value of each World War II factor was modified, if necessary, to fit the conditions anticipated in the campaign under study. It was possible to use certain factors without change; it was possible to predict, with reasonable assurance, changes in others; for some others there was no way to predict specific values, thus a range of values estimated to bracket the probable value was used.

The final product of the study was two-fold. First, a reasonably reliable answer to the original question was obtained. Secondly, a method was devised to produce quantitative estimates for war plans. The model described is a force requirements model (adapted to a capability study), but a major portion of it dealt with combat attrition. As the campaign under study becomes further removed in time from reasonably comparable combat experience this portion of the model increases both in importance and in difficulty. For these reasons the attrition model has been given intensive study by operations analysts throughout the Air Force, and by Air Targets Division, RAND, the Weapons Systems Evaluation Group, and others.

The attrition model describes in mathematical terms the air battle—the battle between the attacking air force and the defenses. The complexity of the model depends upon the complexity of the air battle, the purpose of the study, and the reliability of the data.

If the purpose of the study is to compare alternative armaments for a particular aircraft type it may be possible to limit the air battle to the duel between a single airplane of the aircraft type under study and a single airplane of the type expected to be encountered by the aircraft type

under study. The model used would be of limited scope but would have to describe in considerable detail the actual duel. In scope it need only cover the action from the time the aircraft are so positioned that a duel can take place until the end of a firing run by the aircraft under study. It would have to contain terms describing the performance of each aircraft, its fire control system, its armament installation, its projectiles, its pilot, its vulnerability, and perhaps other details. It would have to relate these things to time and space, and to each other.

If the purpose of the study is to estimate replacement rates for strategic bombardment aircraft in a future war the model must describe the air battle in which the aircraft is expected to be involved in the future campaign. It must account for numbers and types of targets, attacking bombers (and their formations, if any), escorts (if any), enemy early warning, fighters and fighter control, anti-aircraft defenses, countermeasures and counter-countermeasures. It must account for relative overall effectiveness of armament systems but does not need to describe the details of the duel as discussed above. The model must provide, in addition, a means of estimating our losses on the ground if in the future campaign the enemy will have the capability of attacking our bases.

If the purpose of the study is to estimate the effectiveness of an air defense system the model may be limited in scope to a description of one or more attacking aircraft flying through a typical section of the air defense net. It must account for early warning detection range and probability of detection, number, location, and performance of defensive fighters, capability to control fighters and position them for interception, relative over-all effectiveness of armament systems, counter-measures, and counter-countermeasures. It need not describe the details of the duel.

Simplified models are used where quick estimates are required or crude estimates are satisfactory. It is not justifiable to develop elaborate models when the state of knowledge or the reliability of data are known to be weak. Under any circumstances the model must be developed or adapted for the particular problem under study. It must be kept under constant scrutiny and must be subjected to test at every opportunity.

It will be evident from the above that while attrition models may differ from one another very greatly they, nevertheless, belong to the same family. Models developed by operations analysts at Strategic Air Command differ in considerable detail from those developed by analysts at Air Defense Command. Both of these differ from those developed at Headquarters USAF. But they all have the same aim: to describe mathematically an air battle with sufficient precision that they will produce realistic estimates of probable attrition in such a battle. The work of each operations analysis office working on the attrition problem has contributed to the progress of all the others.

The earliest models, developed and used in 1946 and 1947, were tested using combat data from World War II. Since that time World War II data have become less and less useful for this purpose, because the air battles the models are intended to describe resemble World War II air battles less and less. Attempts to use combat data from Korea have not been very satisfactory because of the limitations surrounding Korean air combat and the in-

completeness of the data obtained from the air battles that have been fought. In spite of this, it has been possible to determine that the model intended to describe the air battle between B-29 type bombers and jet interceptors is reasonably reliable, using the data from the small number of battles between B-29's and MIG-15's.

(2) Weapons Effectiveness. During World War II every operations analysis section with a combat command engaged in bombing operations was called upon to study weapons effectiveness. The term weapon, as used here, means the combination of a bomb and a particular fuze setting. The purpose of weapons effectiveness studies was to determine which weapon, or combination of weapons, was best for each target type. The results of such studies would serve as a guide in selecting the weapons for future attacks.

One source of weapons effectiveness data is the continuing program of tests carried out at military proving grounds. The greatest source of data, however, was careful study of reconnaissance photography obtained by allied bombardment aircraft on missions and by reconnaissance aircraft flying over the targets both before and after the attacks. Some information was obtained from a study of our own targets which had been attacked by enemy aircraft. Toward the end of the war it was possible for analysts to follow our advancing armies and to study, on the ground, the targets we had attacked. Information from these varied sources did not always agree, and in any case the information was inadequate for completely reliable weapons selection.

Immediately after World War II the Operations Analysis Division in Headquarters USAF prepared a report which summarized the weapons effectiveness data from World War II and presented methods and data for weapons selection for a wide variety of targets. This report was used by the Air Force as the basis of its current manual on weapons selection, AFM 200-5.

An important by-product of the report just mentioned was a clear pointing up of the areas in which information was incomplete or lacking. Recommendations were made for additional research to fill in the gaps in our knowledge. As a result of these recommendations, contracts were negotiated with Lehigh University and with Purdue University for the necessary research.

Effects of Atomic Bombs. The initial use of atomic bombs came so late in World War II that a very limited amount of information relative to the effectiveness of these weapons was obtained from combat experience. Therefore, it has been necessary to do a great deal of research to obtain information on the effectiveness of atomic bombs against a variety of possible future targets. Operations Analysis has done some theoretical work in this field but the major effort has gone into the design and analysis of the Air Force part of the long series of atomic bomb tests. The Operations Analysis participation in this work has been largely by the offices at Headquarters USAF and Strategic Air Command.

Considerable work has been done on the expected effects of atomic and nuclear bombs on the delivery aircraft. The analysts at Strategic Air Command were pioneers in this field but have been joined in this work by analysts at Headquarters USAF and Tactical Air Command.

(3) Air Defense. Another major field of activity of Operations Analysis is the study of air defense. The Operations Analysis Division in Headquarters USAF has a continuing re-

sponsibility in the field of air defense and has made several specific studies. One of these was a study of the probable effects of a Soviet A-bomb attack on the continental United States, and another dealt with the defense of USAF bases in England. The specific results of these studies are highly classified, but recommendations were made for immediate action as well as for some long-range developments. Action has been taken on a number of these recommendations.

The major effort in the air defense field is that of the Operations Analysis Office at the Air Defense Command. The Air Defense Command analysts are making exhaustive studies of the air defense of the continental United States. This is their only responsibility. They have subdivided the air defense operation into three major parts: detection of enemy aircraft, identification of enemy aircraft, and interception of enemy aircraft. Through intensive theoretical study and analysis of air defense exercises they have succeeded in discovering means of making major improvements in these three parts of the operation. A recent report covering the work of approximately fifteen months resulted in a proposed major modification of the procedures for identifying aircraft penetrating the eastern and western borders of the continental U.S. from over the sea. The purpose of the modification was to reduce the probability of mistaking a hostile aircraft for a friendly. Test results indicate that the proposed system will reduce that probability substantially to that of pure chance, and, in effect, will solve the problem of aircraft identification.

Operations analysts in Japan and Alaska are also studying the air defense problem. By prompt and efficient exchange of information among the analysts working on the air defense problem, improved methods developed in one command are promptly applied to the others, where they are applicable.

(4) Jet Fighter Accidents. Early in the post-World War II period one of the problems brought to the attention of the operations analysts at the Tactical Air Command was the difficulty experienced by pilots in making a parachute jump from a disabled jet fighter. Analysts made a thorough study of jet fighter accidents. Data indicated a high incidence of head injuries among pilots in getting out of disabled jet aircraft. This led to a theoretical study of probable trajectories of the canopy when released by the pilot prior to his jumping from the aircraft. The study showed that the most probable trajectory of the canopy was such that the canopy would strike the pilot's head.

Recommendations were made that special helmets be furnished the pilots immediately and that the canopy be redesigned so that it could not follow such a trajectory. Another result of the study of accidents was a recommendation for the redesign of the wing-tip tanks in order to furnish greater stability to the aircraft in flight. These recommendations were accepted and action resulted.

(5) The Korean War. The Operations Analysis Office of the Fifth Air Force, in the Spring of 1950, was making an intensive study of the air defense system of Japan. When the fighting began in Korea, the mission of the Fifth Air Force changed overnight from a defensive one to an offensive one. Just as quickly the operations analysts of the Fifth Air Force abandoned their study of the air defense of Japan and went to war with their command. During the first few weeks of the war, while the Fifth Air Force was building up its strength in experienced tactical com-

bat officers, the analysts worked as targets-and-weapons staff officers. They selected specific targets, and weapons for those targets. They analyzed the results of the early attacks and recommended a variety of improvements in the early operations. When the allied armies broke out of the Pusan perimeter, the analysts formed ground survey parties to examine the targets we had attacked and to analyze the effects of those attacks. The Fifth Air Force analysts are making continuing studies of current operations. The primary purpose of these studies is to improve current operations. A secondary and very important purpose is to analyze the experience of the Fifth Air Force in using equipment untried in combat prior to the Korean War. An example of this is the jet combat between the F-86 and the MIG-15.

(6) Design of Test Operations. In times of peace or cold war the Air Force must rely on test operations for performance data on rapidly developing new weapons and equipments. Operations analysts design many such operations. The first real test of the capability of the B-36 was designed by an operations analyst of Headquarters USAF. It is essential in such tests to simulate as closely as possible combat conditions, and to interpret the results of the test realistically. Operations analysts at SAC, TAC, ADC, and AAC are called upon frequently to design training operations of their commands and to analyze their results. Analysts at the Air Proving Ground Command and the Special Weapons Center design and analyze operational suitability tests.

(7) Advisory Assistance. Operations analysts act as scientific advisers to their commander and his staff. Each operations analyst gives much informal advisory assistance to officers in his headquarters and in subordinate operating units. It is inevitable, and not undesirable, that much of the work of operations analysts is never formally recorded.

F. Summary. Operations analysis is the scientific study of operations for the primary purpose of providing a quantitative basis for decisions regarding the improvement of the operations. Important by-products of such studies are, (1) the discovery of needs for new or modified equipment, weapons, tactics, etc., which may be translated into requirements by the proper staff agency, and (2) the development of quantitative planning factors of use to the war planners. Operations Analysis in the USAF is an organization which makes such scientific studies. AFR 20-7 authorizes Air Force commanders to establish operations analysis offices in their commands if they wish to, but places the responsibility of selecting and indoctrinating all operations analysts in the Operations Analysis Division, Headquarters USAF.

AIR FORCE REGULATION NO. 20-7 DEPARTMENT OF THE AIR FORCE WASHINGTON, 6 MAY 1953

ORGANIZATION—GENERAL

Operations Analysis

1. **Purpose and Scope:** To define the mission and functions of Operations Analysis and to authorize the establishment of Operations Analysis offices in the Air Force.

2. **Mission:** Operations Analysis will provide commanders and staffs with ready and informal access to scientists with specialized training in the techniques applicable to the analysis of the air warfare; will analyze the problems of air warfare with the objective of improving equipment, weapons and weapons systems, tactics, and strategy; and will furnish, wherever possible, a quantitative

basis for command and management decisions.

3. **Organization:**
   a. *Headquarters USAF.* Operations Analysis is a division of the Directorate of Operations. The Chief of the Operations Analysis Division will be a civilian, and will be responsible for the general direction of the Operations Analysis program, and for the administration of the Headquarters USAF, Operations Analysis Division.
   b. *Major Air Commands.* Commanders of major air commands are authorized to establish Operations Analysis offices in their headquarters within their authorized personnel ceilings. Each Operations Analysis office will be directed by a civilian chief. When an Operations Analysis office is to be established in a command, the commander will inform Headquarters USAF, of the number of analysts needed and the technical specialities desired. The assistance of the Operations Analysis Division, Headquarters USAF, may be requested in determining these requirements.
4. **Functions:**
   a. *Headquarters USAF.* The Operations Analysis Division will:
      (1) Keep Headquarters USAF informed of the activities and results of all Operations Analysis offices.
      (2) Make scientific studies of Air Force equipment, weapons and weapons systems, tactics, and strategy as requested by the Air Staff and other Air Force organizations.
      (3) Monitor and coordinate programs of all Operations Analysis offices.
      (4) Maintain a flow of scientific and technical information between Headquarters USAF, all Operations Analysis offices, and other research activities.
      (5) Provide assistance to major air commands in the recruitment of operations analysts.
      (6) Select, indoctrinate, and recommend assignment of all operations analysts employed by the Air Force
   b. *Major Air Commands.* Each Operations Analysis office will make scientific studies of equipment, weapons and weapons systems, tactics, strategy, organization, and so forth, as directed or approved by the commander of the command to which it is assigned, and will keep the commander and his staff informed of scientific and technical developments related to the fulfillment of the mission of the command.
5. **Studies:**
   a. Operations analysis studies are not limited to specific subject matter fields, but may be concerned with the fields of responsibility of any one or more staff offices or Air Force activities. Reports and memoranda presenting results of analyses by operations analysts do not necessarily express Air Force policy and are not subject to the staff coordination required for policy documents prior to publication and distribution.
   b. All activities of the Department of the Air Force will furnish advice and assistance to each Operations Analysis office upon request; will furnish or give access to all existing reports and data required by the work of the office; and will facilitate visits of operations analysts to installations of the Air Force and other organizations as required by the work of the office.
6. **Communications:** Direct communication is authorized between Operations Analysis offices for exchange of information and data, including classified information and data, and on other non-policy Air Force business. The normal medium will be the official personal letter. Communications of a policy nature will be through command channels. Requests for operations analysis studies will be addressed to Director of Operations, Headquarters USAF, ATTENTION: Operations Analysis Division, Washington 25, D.C.
7. **Identification:**
   a. Operations analysts carry WD AGO Form 65, Identification Card.
   b. Operations analysts will be issued, in addition to WD AGO Form 65, a second identification card, DD Form 489, Noncombatant's Certificate of Identity, under either of the following conditions:

(1) When assigned to an Air Force unit in a combat zone, on full time or temporary duty.

(2) When assigned to an Air Force unit which may have to move into a combat zone on short notice in event of war. In this case, such identification forms will be stored in the office of the chief of the Operations Analysis office concerned and will be issued to the analysts only on departure of the individual for a combat zone.

c. Operations analysts will furnish evidence of security clearances, as required, through proper channels.

8. **Uniforms:**

a. Operations analysts are authorized to purchase and wear the official Air Force uniform only under the following conditions:

(1) While assigned to a command in a combat zone, on full time or temporary duty. The uniform may be worn while traveling to and from the combat zone.

(2) While assigned to an oversea command, on full time or temporary duty, if prescribed by the commander of the command to which assigned. The uniform may be worn while traveling to and from the oversea duty station.

b. Operations analysts assigned to Air Force units which may have to move into combat zones on short notice in event of war may purchase uniforms on the authority of commanders of major air commands concerned. Uniforms will be worn only in the event such action takes place.

c. When prescribed, the Air Force uniform will be worn as follows:

(1) All insignia, insignia braid and USAF buttons will be removed from the uniform. USAF buttons will be replaced with plain, commercial-type, dark blue composition buttons.

(2) All garments of the Air Force uniform may be worn except the service cap (with visor). Only the flight cap, without insignia braid, may be worn.

(3) Identifying cloth patches, described in (4) below, will be worn on the right shoulder sleeve of all outer garments, ½" below the shoulder seam and on the left front of the flight cap, 1" to the rear of the front center line.

(4) Identifying patches will be rectangle of blue shade 83 background, 2½" in height and 3" in width with a gray shade 155 equilateral triangle 3¼" bearing the letters "U.S." in blue shade 83, ¼" in width and ¼" in height. The patch will also indicate the designated assignment in gray shade 155 letters ½" in height evenly spaced of "AF Operations Analyst" arranged above and below the triangle.

9. **Reports:** The commander of a command having an Operations Analysis office will inform Headquarters USAF of the activities of his office and of results obtained. This may be accomplished through courtesy copies of summary reports if such reports are prepared by the chief of the office for his commander. These reports are exempt from the requirements of Reports Control Symbols in accordance with paragraph 9a, AFR 174-1, 9 August 1951, and will be forwarded, if available, to the Director of Operations, Headquarters USAF, ATTENTION: Operations Analysis Division, Washington 25, D. C.

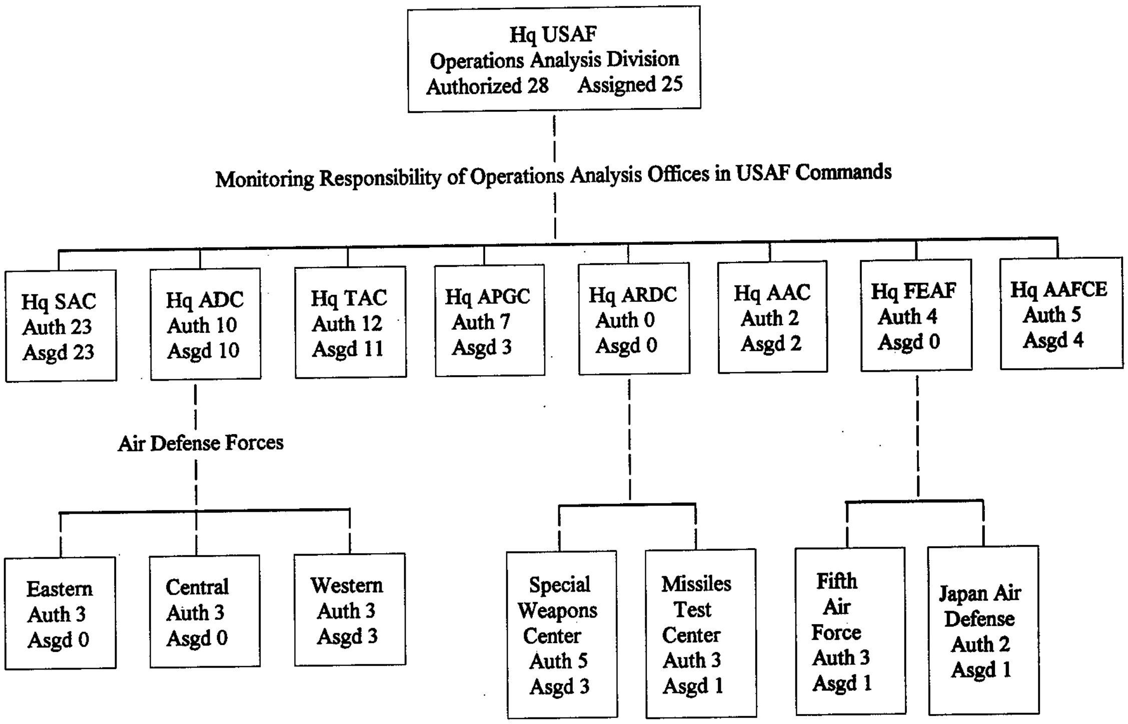
BY ORDER OF THE SECRETARY OF THE AIR FORCE:

HOYT S. VANDENBURG
Chief of Staff, United States Air Force

OFFICIAL:

K. E. THIEBAUD
Colonel, USAF
Air Adjutant General

APPENDIX: OPERATIONS ANALYSIS IN THE USAF (September 1952)



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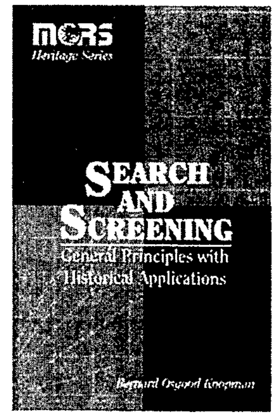
Search and Screening:
General Principals with Historical Applications
Bernard Osgood Koopman



Search and Screening is the second reprint in the MORS Heritage Series. Dr. Bernard Osgood Koopman has played a significant role in the military operations research profession. Along with Dr. Kimball, co-author of our first classic (*Search and Screening*), he helped to pioneer the modern theory of search as applied in World War II and designed many naval operating plans. In 1979, he became the second recipient of the MORS Vance R. Wanner Memorial Award, presented to those who have played a major role in strengthening the profession.

This publication has enduring value because as stated in the preface of this book, even though this volume has long been out of print, "extracts and translations of parts of it are being used both in the United States and in many other nations giving scientific naval instructions." Since its original print, it has continually been updated. One of the individuals mentioned in preface who has "helped make important improvements" is CAPT **Wayne Hughes**, USN, (Ret) (MORS Past President, MORS Fellow and Wanner Award recipient). MORS' roots are truly evident in this book.

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Modelling the Mobile Land Battle: Combat Degradation and Criteria for Defeat

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OR METHODOLOGY: Simulation

APPLICATION AREA: Land Warfare and Measures of Effectiveness

INTRODUCTION

This is the third in a series of articles focusing on the mobile land battle. The first (Speight, 1995) identified four key features which, based on the evidence of field trials and of actual combat, seemed likely to have a major influence on the manner in which such battles may unfold. These were: the formation of mini-battles within each engagement; the acquisition of targets as a function of each mini-battle's circumstances; the effects of combat degradation; and the criteria used to decide whether one side or the other had been defeated. The second article (Speight, 1998) used a battle simulation to explore in more detail the first two of these issues: mini-battle formation and the acquisition of targets. In addition an assessment was made of the extent to which model predictions could be accommodated within the traditional Lanchester frame of reference. The present article now concentrates on the last two issues: combat degradation and defeat criteria.

For each topic in this series the plan of action has been the same. First, the evidence from trials and from war records has been reviewed; next, modelling proposals have been put forward to represent the major features and relationships identified within the review; and, lastly, the predictions of the resulting battle model have been evaluated. One of the main evaluation approaches has been to try and reconcile the model outputs with classical Lanchester theory. The results so far suggest that, although the Lanchester approach via differential equations is not well suited to the portrayal of detailed interactions at the tactical level, the state equations may perform tolerably well as a summary device. These equations eliminate the time dimension and instead concentrate only on the expected balance of attrition. Obviously, in their most simple and literal form, Lanchester formulations with constant coefficients are highly unlikely to mirror the expected course of attrition in mobile engagements. Simple Lanchester equations will predict a steadily declining casualty rate with time as the numbers of survivors decrease. However, due to the variation of line-of-sight probabilities and other separation effects, the bulk of casualties in mobile engagements will tend to occur after some time has elapsed, when the ranges between the combatants have closed. This problem can be circumvented by eliminating or transforming the time dimension. Nevertheless, even when this is done, the fact remains that the attrition from a mobile battle will generally be the aggregation of that from a collection of mini-battles, each with different odds and numbers of participants, each at a different mean range and, hence, each with different target acquisition delays and kill probabilities. For a 'pseudo-Lanchester' approach to be practically useful it must be possible to postulate a simple, unvarying 'equivalent' attrition process, the parameters of which may then be linked to the 'average' circumstances of each engagement in at least a rough and ready way. This casualty-producing process, when exercised, should then reproduce reasonably closely the aggregated attrition relationships observed in more detailed simulations or in real life. In the last paper it was shown that, at least in the clinical and controlled world of the computing laboratory, it was possible to devise a 'pseudo-Lanchester' approach which met these conditions. The state equation corresponding to a law dubbed 'Search with Overkill' provided a fairly close fit to the averaged simulation data, better at least than the commonly used 'Power Law' alternative. In addition, the values of the best-fit parameters for the former did seem to relate in plausible fashion to changes in the simulation assumptions.

With both of the topics in this paper we shall follow the established pattern of review, devising model constructs and then evaluating simulation outputs. The study of how men behave in battle must be a virtually inexhaustible field of enquiry. The results set out here represent just one attempt to quantify in simple fashion some of the findings of historical analysis, and to judge whether they can then be accommodated sensibly within a wider framework of traditional battle modelling. Given the incomplete nature of the data available so far there is some room for speculation. The concluding section of the paper, dealing with defeat criteria, will be even more speculative and qualitative. There is, of course, nothing in the Lanchester formulation which deals explicitly with victory or defeat. However, because it is a theory concerned with the dynamics of attrition, it has probably been influential in prompting approaches couched exclusively in terms of casualties or of relative force strengths. Although there has been much analysis linking these two factors to assessments of victory or defeat, little seems to have emerged in the way of clear cut relationships. The present paper puts forward, not a recommended recipe for future modelling algorithms, but an initial exploration and discussion of one alternative approach to the

portrayal of this phenomenon at the tactical level of combat.

COMBAT DEGRADATION

It is commonly accepted that military performance in actual battle tends to be significantly worse than that normally achieved in peace time conditions. The causes of such degradation may include:

Task differences. The operational task itself may differ in certain respects from nominally the same task in peace time circumstances. Thus, Rowland (1986, 1987) found that much of the reduction in infantry firing performance in trials, as compared to that on the practice range, could be attributed to such details as different target acquisition conditions, motion characteristics, exposure times, etc.

Deterioration of military skills. Military skills may deteriorate under the stresses and intense stimulation of war. One of the most venerable relationships established in experimental psychology is the so-called 'inverted-U hypothesis' or Yerkes-Dodson law, named after the investigators who first demonstrated the effect in animal learning experiments (Yerkes and Dodson, 1908). This law holds that there is an optimal level of arousal for any given task. The more difficult the task the lower will be this optimal level of arousal. Naturally, most of the systematic evidence in support of this hypothesis arises in fields other than that of battle, such as the academic or sporting arenas. However, there can hardly be a more arousing environment than that of direct mortal combat. According to the Yerkes-Dodson law one would thus expect the most difficult military tasks to be seriously degraded in battle; while the simplest (especially if they require just brute strength) could actually be enhanced. There is a copious literature on this topic, but the following is a selection of relevant references: Broadhurst, 1959; Covington and Omelich, 1987; Duffy, 1962; Jackson, Buglione and Glenwick, 1988; Landers, 1978, 1980; Martens, 1974a, 1974b; Martens and Landers, 1970; Näätänen, 1973; Sarason, Sarason and Pierce, 1990; Weinberg and Ragan, 1978.

Active contribution to battle. Irrespective of any deterioration of skills, there may be a refusal, or inability, to exercise them under conditions of direct warlike threat. This source of degradation is not necessarily independent of the previous one, since a possible mechanism of skill impairment under intense arousal is that of 'paralysis' of thought or action (see, e.g., Tyhurst, 1951).

In what follows we have attempted to use as our baseline of military performance that measured in 'realistic' tactical trials, hoping in this way to minimise any effects due simply to task differences in peacetime and wartime conditions. When this has not been possible we have had to make direct recourse to battle data, supplemented by some simple hypothesis to link these latter to the inferred trials baseline. In this paper we have assumed that 'combat degradation' arises from the confounded effects of the last two broad factors mentioned above. Our estimates are certainly broad brush, capable of considerable refinement. However, it seems unlikely that a comprehensive and fully quantified theory of all aspects of combat degradation will ever be assembled. Not only is the catalogue of military skills and the way that they may interact in task performance almost inexhaustible, but it is impossible to mount ethical assessment experiments in conditions closely mimicking those of war. Since the emphasis in this paper is on modelling, rather than on combat degradation *per se*, the review which follows makes no pretence of being anything like a comprehensive account of what is known about performance in battle. In particular, no attempt will be made to speculate on causes, or on other factors which may be associated with, or affect, the level of combat degradation actually achieved in battle. Fuller accounts of this kind can be found in Rowland, 1996; Rowland and Richardson, 1997; and Rowland and Robinson, 1997.

The Evidence from Trials and Battle

Although this paper is concerned mainly with armoured warfare, brief mention will be made of the infantry battle because there should at least be some read across from the latter to the former.

The Infantry Battle - The Evidence from Trials. As has already been mentioned above, Rowland (1986, 1987) established that defensive firing performance in close-combat trials was worse than that achieved on the practice range. The degradation was roughly a factor of 10 for

rifles and 6 for machine guns. In realistic trials there was a linear relationship between the kill rate per defender and the local force ratio (so that kills per defender rose in direct proportion to the number of attackers present). This appears to confirm the importance of the target acquisition process as a major determinant of achieved firing performance. The number of kills per defender was distributed in approximately log normal fashion, with a standard deviation roughly equivalent to a factor of 2. Although the regression coefficient of kill rate on force ratio was significant, it did not account for all the between-individual variance. This latter was presumably due both to differences in firing opportunity and to differences in skill levels.

The Infantry Battle - The Evidence from Battle. A pioneering study of behaviour in battle was that conducted by Brig Gen Marshall (1947), based on an extensive programme of post-combat interviews of U.S. troops. He concluded that only some 15% of the infantry population could be relied upon to make any direct contribution to the defensive battle, although the degree of participation was likely to be rather higher than this figure for machine gun crews and rather less for riflemen. Lt Col Wigram (1943) was a British officer who pioneered realistic 'battle inoculation' training methods. He was later given a number of field command positions in Sicily, being charged with the production of proposals to refine these methods, based on the direct observation of battlefield performance. He too stressed the reality of individual differences in this connection, characterising this in the following words: "Every platoon can be analysed as follows: six gutful (*sic*) men will go anywhere and do anything; twelve 'sheep' who will follow behind if they are well led; and four to six men who will run away." The report was felt to be over-critical and bad for morale, and its findings were suppressed until after World War II.

Rowland and his colleagues undertook a very extensive series of quantitative historical analyses of the infantry battle, comparing performance with that achieved in tactical trials. Some early results are given in the two publications already referred to (Rowland, 1986, 1987). Battlefield performance, in terms of casualties inflicted on the attacking force per defending weapon, was about one tenth of that typically achieved in trials. It was not possible from this aggregated data to attribute the degradation directly to individual differences of behaviour. As has been alluded to by Lidderdale (1991) and Speight, Rowland and Keys (1997), further research has shown that, when battle effectiveness is measured in this way, different armies have their own typical performance levels. These levels have proved remarkably stable over the years and from one battle to another. In infantry warfare, at least, this kind of collective degradation shows itself clearly only in the defensive battle and not in the attack.

Armoured Warfare - The Evidence from Trials. Mention has already been made in Speight (1997) of the various armoured warfare trials which have yielded the key modelling relationships employed in this study. The group of British free-play tactical engagements known collectively as Exercise CHINESE EYE (see, e.g., Rowland, 1984) has been especially significant. It is important to note that in CHINESE EYE, just as in the British infantry trials, the number of kills per defending weapon system was distributed in approximately log normal fashion, with a standard deviation roughly equivalent to a factor of 2.

Armoured Warfare - The Evidence from Battle. Analysis of historical records has shown that the effectiveness of rifles and machine guns has altered but little over recent years. This has made it relatively easy to compare infantry performance in post-War trials with that achieved during World Wars I and II. The same certainly cannot be said for anti-armour weapons. Accordingly, rather than using CHINESE EYE directly as a benchmark, estimates of degradation in armoured combat have been built up by direct recourse to wartime records. Core estimates have been obtained from a very detailed analysis of two World War II battles in the Western Desert (Rowland, 1992; Rowland, Dixon and O'Connor, 1997), plus a smaller sample of engagements from the Greek campaign. All these were essentially actions in which attacking tanks were opposed by anti-tank guns. Very full accounts were available in these cases, and it was possible to associate all

the enemy casualties with individual guns. The detailed analyses were then supplemented by broad-brush analyses from a large sample of battles in which only summary data were available.

The main point to emerge from the detailed analyses was the major variation in contribution to the defensive battle made by the different gun crews. The 21 percent of crews in which at least one member received a subsequent award of VC (Victoria Cross), DSO (Distinguished Service Order) or DCM (Distinguished Conduct Medal), or MC (Military Cross) or MM (Military Medal), inflicted more than five times as many casualties per target per engagement as did the remaining 79 per cent. Of the less effective proportion, one in three made no contribution at all. The hypothesis put forward to link the observed level of combat performance to the notional trials baseline was that gun crews may be roughly grouped into three levels of battle contribution: 'heroes' or 'fully active' (identified by the fact that at least one crew member subsequently received an award for gallantry); 'partially active' and 'inactive'. Based on these results 'heroes' may be expected to make a contribution equivalent to that normally achieved in trials; the 'partially active' will make a contribution at roughly one third this level; and the 'inactive' will make no contribution whatsoever. This is almost certainly a conservative hypothesis, not only because it assumes that 'heroes' are subject to no degradation at all, but because the small number of battles in this sample are all successful defensive engagements. This view of combat degradation sees performance in battle as being affected by three broad factors: skill; opportunity; and willingness, or ability, to make a contribution given that an opportunity occurs. The first two sources of variability will be reflected in performance during peacetime trials; but the third, additional, source will affect performance only in battle. If this view is correct, we should expect the variance within the 'hero' and 'partially active' subsamples to approximate the whole-sample variance normally observed in trials (the variance of achieved performance of the 'inactive' subsample being, of course, zero). The analysis showed that this was indeed the case. Although the means for the 'hero' and 'partially active' subgroups differed markedly, within each subgroup the number of kills per defending weapon system was distributed in approximately log normal fashion, with a standard deviation roughly equivalent to a factor of 2.

For these few historical armoured actions very detailed information was preserved. For a much larger World War II sample (including successful and unsuccessful actions, in NW Europe as well as the Western Desert) the more usual summary data were available. On a 'per engagement' basis the aggregated results yielded an overall relationship which was consistent with the detailed picture given above:

$$E = 0.2 + 0.8(\text{'heroes' per gun})$$

where E is the expected level of 'defence effectiveness', measured in terms of kills per defender and scaled so that $E = 1$ when the 'heroic' manning level was one per gun. The results also showed that the 'defence effectiveness' of towed guns was significantly higher than that achieved by tanks. Possible reasons for these empirical results, as well as details of samples and analysis, are given in Rowland & Richardson (1997).

A large amount of parallel research has shown that, just as in the infantry battle, there are very significant and stable differences in the ability of different armies to inflict casualties on their opponents. The average level of 'defence effectiveness' for armoured warfare appears on the whole to be remarkably similar to that army's 'defence effectiveness' in the infantry battle. First indications are that, unlike the infantry battle, these assessed armoured effectiveness levels are also reflected in attack performance, although the effect is much less marked. In addition, differences in attacking performance do not seem to be as regular and consistent as do the defensive differences.

A Modelling Approach to the Phenomenon of Combat Degradation

A most salient and striking feature of the evidence from historical records is that of indi-

vidual and collective differences. Some soldiers function at an heroic level; others appear to make an intermittent contribution if they are well led; and yet others seem incapable of utilising their learned skills under the immense stresses of battle. This state of affairs is very much at variance with the basic tenets of Lanchester theory. Our modelling aims in this paper are very limited. No attempt has been made to produce absolute predictions, or to simulate all the different nuances of battlefield behaviour. The intention is just to incorporate a simple representation of this variation in our model of armoured warfare. This will then represent a provisional hypothetical framework, to be tested against additional historical outcomes. A programme of 'laboratory experimentation' using this Monte Carlo simulation should yield some first impressions as to the manner in which combat degradation may affect battle outcomes; and whether or not this effect can easily be accommodated within the Lanchester frame of reference.

The representation of combat degradation effects outlined below was incorporated into the Monte Carlo simulation described in Speight (1998), using the mini-battle formation and target acquisition logic developed there. The simulation depicts a schematic tank *versus* tank engagement in which both attacking and defending tanks can be in one of four engagement states: searching for targets; laying or aiming, given that a target has been detected; observing fire; or destroyed.

A basic postulate of the scheme for representing degradation is that, under the threat of live combat, there is a notional dimension of willingness or ability to contribute to the battle. Weapon crews may be roughly grouped into three classes, 'heroes', 'partially active' and 'inactive', according to their standing on this dimension. The probability of crews within these classes responding appropriately each time they acquire a target is set out in Table 1. The defence probabilities are based directly on the detailed historical analysis outlined above. The attack probabilities are arbitrarily assigned. Their values are in accord with the observation that the degradation factor appears to be less in attack: hence the assumption that, since in a mobile engagement they are openly committed, all attacking crews will have a lesser disincentive to fire. In the simulation weapon crews were designated as 'heroes', 'partially active' or 'inactive', the probability of transiting from 'search' to 'lay' following a target detection then being as set out in Table 1.

Table 1. Assumed per-detection probability of response for different categories of weapon crew

	'Inactive'	'Partially active'	'Heroes'
Defence	0.0	0.3	1.0
Attack	0.05	0.5	1.0

A further postulate of this degradation scheme is that the parent populations of weapon crews of different armies are differently distributed along the notional 'ability to contribute in battle' dimension. For want of any more definitive evidence it has been assumed that this propensity is normally distributed, different populations having the same standard deviations but different means. Figure 1 illustrates this assumption for three different, entirely hypothetical, parent populations. The illustration has been scaled so that 'Population 1' has zero mean and unity standard deviation. On this scale the 'inactive - partially active' threshold is set at -0.67 and the 'partially active - heroes' threshold at $+0.85$. The mean for 'Population 2' is at -1.0 and for 'Population 3' it is at -1.7. Table 2 translates these assumptions into the assumed proportions of the different weapon crew categories in each parent population. The 'defender participation' (*DP*) and 'attacker participation' (*AP*) indices are included to give some indication of the relative battle contribution to be expected of each population in defence or attack. However, it should not be assumed that these simple-minded indices translate in straightforward linear fashion to other indicators of collective performance (such as kills per weapon system per engagement). 'Population 0' represents the notional 'peacetime trial' baseline, in which all weapon crews perform as 'heroes'.

This representation of the effects of combat degradation is almost certainly simplistic. Consideration might be given to the following points in producing a more complete representation:

> The outlined scheme makes the probability of response to a detection independent of any other factor. It seems plausible to suggest that in practice it may be affected by the perceived starting odds and by the apparent severity of immediate threat at the time of detection.

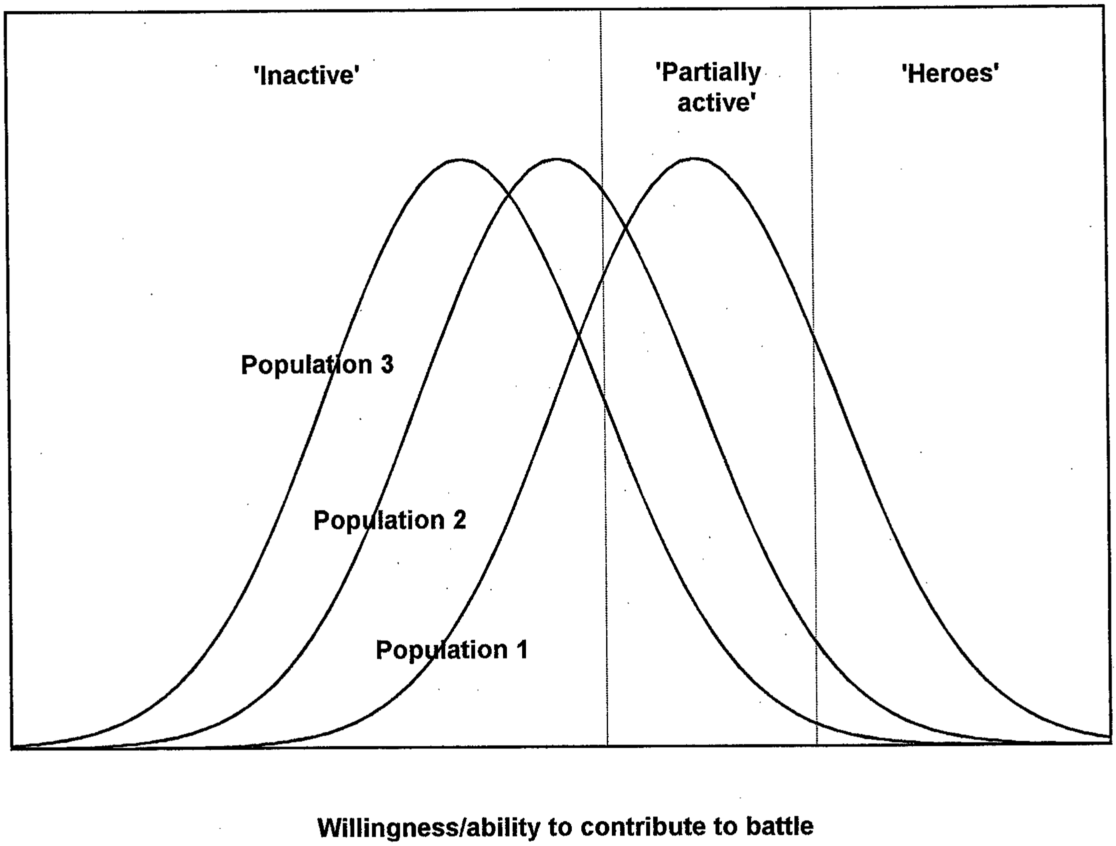

Figure 1. Distribution of three different hypothetical weapon crew populations along the 'contribution to battle' dimension.

Table 2. Assumed proportions of weapon crew categories for hypothetical parent populations. '*DP*' and '*AP*' are the population 'defender' and 'attacker participation' indices: simply the proportions in each weapon crew category weighted by the corresponding probabilities of response. ('Population 0' represents the assumed level of performance for all populations in 'realistic' peacetime field trial conditions.)

Population	'Inactive'	Proportion 'Partially active'	'Heroes'	*DP*	*AP*
0	0.0	0.0	1.0	1.0	1.0
1	0.25	0.55	0.2	0.365	0.488
2	0.6276	0.3396	0.0328	0.135	0.234
3	0.8474	0.1471	0.0055	0.050	0.121

Prior conditions, such as artillery suppression, surprise or the judged campaign situation, may have significant effects.

The outlined scheme assumes that non-responding weapons are still tactically deployed, and have the same visibility and vulnerability as non-firing responding weapons. This assumption may not hold true in real life.

The experiments described below depict battle runs which all terminate at the moment that the attackers close to within 100m of the defenders. No account was taken of the possible consequences, or timing, of mission failure by either side.

Above all, additional hard data would reduce the areas of speculation.

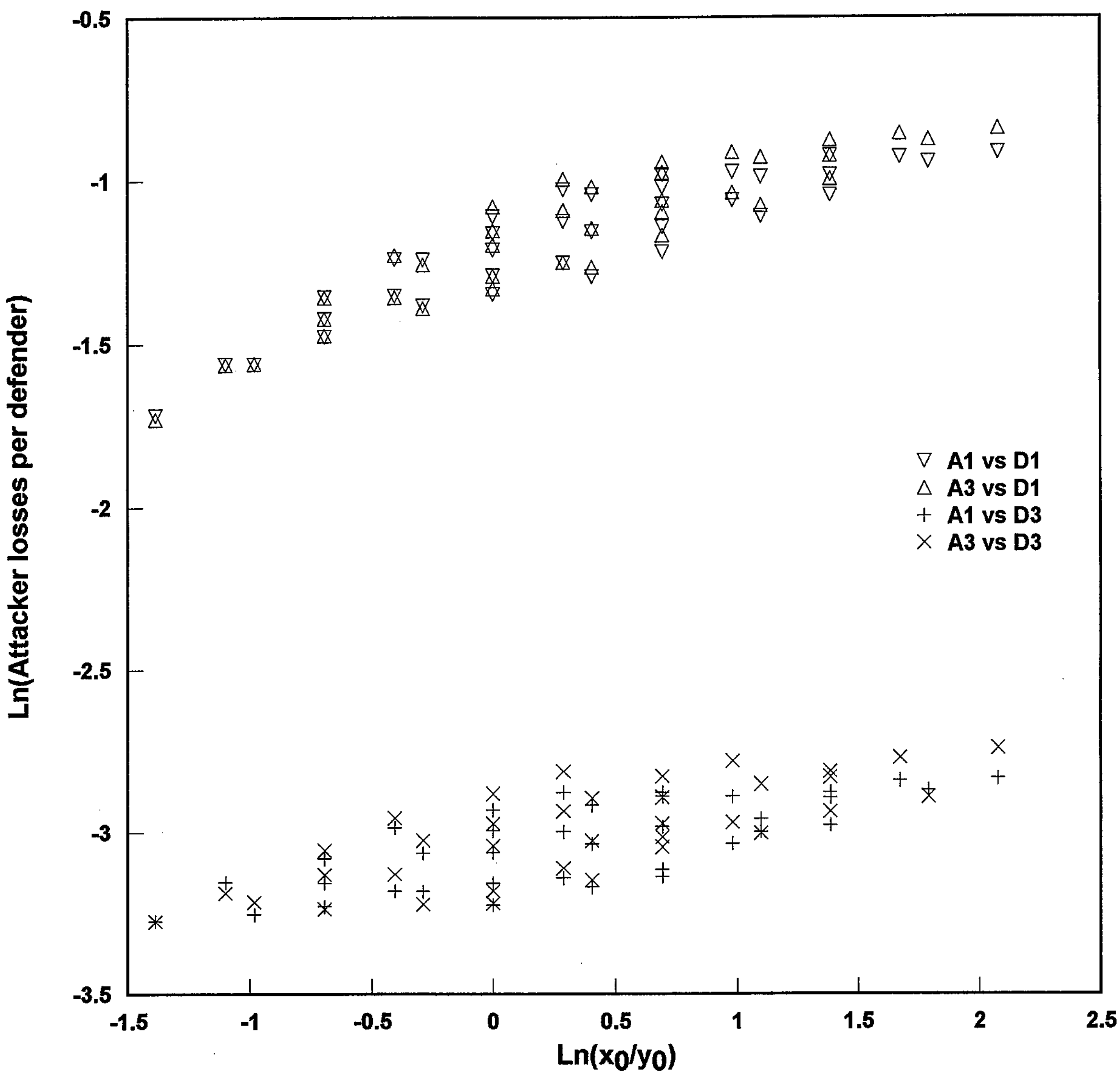

Figure 2. Attacker casualties per defender as a function of initial force ratios. (Here x_0 and y_0 refer to the starting numbers of attackers and defenders respectively.)

Experimental Plan

The battle simulation was run under 13 different experimental conditions. In each condition the putative attackers and defenders were sampled from a different combination of the hypothetical parent populations defined in Table 2. If we denote *A0* to *A3* as conditions in which the attackers were sampled from Populations 0 to 3 and, similarly, *D0* to *D3* as conditions in which the defenders were sampled from Populations 0 to 3, the experimental conditions included the combination *A0* vs *D0* and all 12 combinations (*A0* . . . *A3*) vs (*D1* . . . *D3*). In each condition 5,000 battle runs were made under each of 36 sets of starting odds: x_0 = 32, 24, 16, 12, 8, 6 (attackers) times y_0 = 24, 16, 12, 8, 6, 4 (defenders). For each run each putative attacker and defender was assigned randomly and independently to the category 'hero', 'partially active' or 'inactive' according to the parent population probabilities set out in Table 2. Their simulation performance was then governed by the assumptions set out in Table 1.

Comparison with Historical Battle Outcomes

In an independent historical research programme an analysis has been made of the publicly available records from a large number of armoured engagements between the forces of different armies. The analysis has been conducted in terms of the achieved kills per defender per engagement as a function of the starting odds. Figures 2 and 3 illustrate the aggregated results from four different conditions from our experimental programme, when they are analysed in this fashion. The comparison with real life is clouded by the fact that, while the basic data are in the public domain, details of the analysis are not. But a qualitative judgement (which can, of course, be checked against independent historical assessments) can be made under the following headings:

Absolute kill rates. The simulation attacker casualties per defender agree remarkably well with historically achieved rates. The defender casualties per attacker are significantly lower

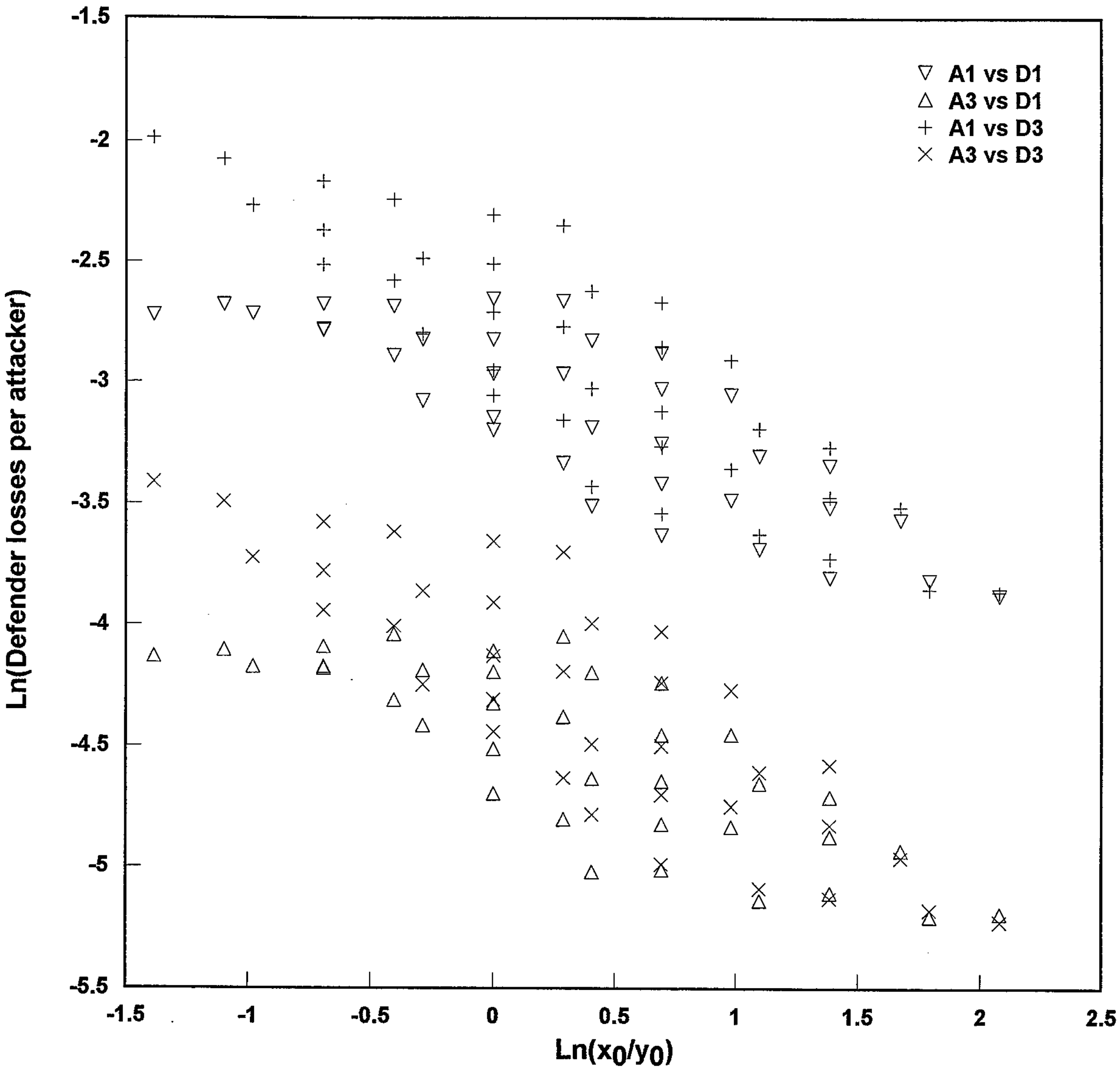

Figure 3. Defender casualties per attacker as a function of initial force ratios. (Here x_0 and y_0 refer to the starting numbers of attackers and defenders respectively.)

in the simulation than they were in real life. One possible candidate cause to account for this difference is that the historical results stem from desert or steppe battles, where the defenders are likely to be a good deal more conspicuous than in the cluttered NW European terrain assumed in the simulation. It should also be noted that the simulation stops short of the terminal phase of each engagement, at which time overrunning attackers could inflict significant casualties on the surviving defenders.

Differences between 'effective' and 'ineffective' forces. Although in **absolute** terms the simulation underestimated attacker (but not defender) kills, in **relative** terms it yielded very similar differences between 'effective' and 'ineffective' forces, both for attack and defence. If the simple '*DP*' effectiveness indices included in Table 2 are taken as being a rough equivalent of the '*E*' 'defence effectiveness' indices assessed for different armies from historical records, then the simulation attrition differences do mirror well kill rate differences noted in historical records. It should be noted that, as appears to be the case in real life, the attacker losses per defender appear to be little affected by the quality of the attacker: the effect stems in the main from the quality of the defender. The rate of defender loss is affected by the quality of the attacking force, but the size of the effect is not so great as the defensive difference.

Kill rates as a function of force ratio. Although the directions of historical trends are in every case the same as those yielded by the simulation, there is a suggestion that 'effective' forces are less affected by force ratio than these results would indicate, and that 'ineffective' forces are more affected. In other words, the kill rates of 'ineffective' forces increase more than do those of 'effective' forces as the odds are stacked increasingly against them. This is **contrary** to the hypothesis that adverse force ratios will heighten the tendency for those more prone to combat degradation to withdraw from the battle. It is possible that adverse odds act as a positive spur to action or, more probably, that the simulation target acquisition logic does not fully mirror the complexities of battlefield detection performance and behaviour.

We have concluded from our limited comparison exercise that, with some relatively minor reservations, the simulation does reproduce tolerably well some of the combat performance relationships noted in actual past armoured engagements.

Combat Degradation and the Lanchester Frame of Reference

In the previous paper in this series it was shown that the state equations from relatively simple pseudo-Lanchester formulations could perform reasonably well as summary devices, capturing the manner in which the expected attrition for each side may vary as a function of the force strengths at the start of the engagement. The two formulations evaluated in the greatest detail were the commonly used 'Power Law' and one dubbed 'Search with Overkill'. Adopting the convention that x and y denote the strengths of the attackers and defenders at a time t, and x_0 and y_0 their starting strengths, the coupled differential equations for the former may be written:

$$dx/dt = -a_1 x^T y^U$$

$$dy/dt = -a_2 x^V y^W$$

for which the corresponding state equation is:

$$(x_0^{b1} - x^{b1})/b1 = b3(y_0^{b2} - y^{b2})/b2 \qquad b1, b2 \neq 0$$

where

$$b1 = V - T + 1$$

$$b2 = U - W + 1$$

$$b3 = a_1/a_2$$

In Speight (1998) the differential equations for the 'Search with Overkill' formulation were written as:

$$dx/dt = -y(x/x_0)/(b8 + b9/x_0)$$

$$dy/dt = -x(y/y_0)/(b10 + b11/y_0)$$

In this idealised view of an engagement kill rates are seen as having a fixed plus a 'search' component, the latter inversely proportional to the total number of targets available, 'dead' or 'alive'. These rates are factored by the chances that the acquired target is already dead. The state equation for this formulation is:

Table 3. Proportional casualties. Overall sums of squares (Sx, Sy) and squared residuals (Rx and Ry as a percentage of Sx and Sy) for alternative pseudo-Lanchester laws; and for different experimental combinations of defender and attacker effectiveness

Attacker Effectiveness		Defender Effectiveness Level			
		D0	*D1*	*D2*	*D3*
A0	*Sx*	2.1266	1.0332	0.2371	0.0391
	Sy	0.2161	0.1908	0.1783	0.1733
A1	*Sx*		0.9946	0.2379	0.0408
	Sy		0.0541	0.0522	0.0520
A2	*Sx*		0.9753	0.2302	0.0393
	Sy		0.0135	0.0131	0.0126
A3	*Sx*		0.9625	0.2349	0.0405
	Sy		0.0037	0.0037	0.0036
'Power Law'					
A0	*Rx*	2.560	0.622	0.700	0.523
	Ry	2.137	1.468	1.070	1.064
A1	*Rx*		1.230	0.392	0.563
	Ry		1.868	1.028	1.016
A2	*Rx*		1.445	0.632	0.522
	Ry		2.740	1.855	1.113
A3	*Rx*		1.421	0.432	0.377
	Ry		1.966	2.024	1.793
'Search with Overkill'					
A0	*Rx*	0.239	0.146	0.160	0.349
	Ry	0.280	0.469	0.516	0.612
A1	*Rx*		0.342	0.121	0.162
	Ry		0.464	0.236	0.612
A2	*Rx*		0.344	0.182	0.334
	Ry		0.878	0.376	0.968
A3	*Rx*		0.557	0.505	0.237
	Ry		1.059	1.361	1.430

$$(x_0 - x)(b8x_0 + b9) = (y_0 - y)(b10y_0 + b11)$$

In the analysis which follows this state equation has been rewritten in three-parameter form:

$$(x_0 - x)/(y_0 - y) = a1(y_0 + a2)/(x_0 + a3)$$

where $a1 = b10/b8$; $a2 = b11/b10$; and $a3 = b9/b8$. It was thought that this format would show up more clearly the manner in which the values of the fitted parameters varied as a function of the different experimental conditions.

As in the previous paper, we have fitted these two pseudo-Lanchester formulations to the simulation results via a nonlinear least squares routine, for each experimental condition minimising the quantity:

$$Q = \sum[\{x' - x)/x_0\}^2 + \{(y' - y)/y_0\}^2]$$

Here x and y are the remaining forces, averaged over the 5,000 runs with initial strengths (x_0, y_0); and the summation is over the complete set of 36 (x_0, y_0) values. x' is the predicted x value, given the form of fitted equation, the assigned parameter values and the observed y value. We define y' in a similar manner. To put the value of Q into some practical perspective, its x and y components have been compared to the within-condition variation of the x and y casualties. For each (x_0, y_0) combination of starting odds we define the average proportional x casualties as

$$p_x = 1 - x/x_0$$

The corresponding overall sum of squares about the mean is then

$$Sx = \sum(p_x - \sum p_x/n)^2$$

Table 4. Fitted parameter values for alternative pseudo-Lanchester laws; and for different experimental combinations of defender and attacker effectiveness

Attacker Effectiveness		Defender Effectiveness Level D0	D1	D2	D3
'Power Law'					
A0	*b1*	1.471	1.474	1.496	1.510
	b2	1.395	1.240	1.166	1.135
	b3	8.907	4.452	2.025	0.825
A1	*b1*		1.468	1.491	1.531
	b2		1.260	1.187	1.126
	b3		8.727	3.933	1.872
A2	*b1*		1.453	1.477	1.517
	b2		1.249	1.179	1.148
	b3		18.076	8.215	3.574
A3	*b1*		1.472	1.506	1.515
	b2		1.257	1.184	1.143
	b3		36.139	16.992	7.180
'Search with Overkill'					
A0	*a1*	7.420	1.586	0.407	0.121
	a2	11.165	25.702	44.020	58.591
	a3	7.348	9.896	12.412	13.971
A1	*a1*		3.356	0.832	0.222
	a2		25.106	43.355	64.964
	a3		9.797	11.676	12.138
A2	*a1*		7.140	1.624	0.486
	a2		25.277	48.211	60.975
	a3		10.291	11.657	11.911
A3	*a1*		13.371	3.003	0.819
	a2		25.666	47.081	71.865
	a3		9.547	10.020	11.122

where n is the number of (x_0, y_0) combinations within an experimental condition. The x component of the squared residuals is

$$Qx = \sum\{(x' - x)/x_0\}^2$$

and the sum of squared residuals, expressed as a percentage of Sx, is

$$Rx = 100Qx/Sx$$

We define Sy, Qy and Ry in similar fashion. In Table 3 we quote the values of Sx and Sy for each of the experimental conditions defined above; and Rx and Ry for each combination of condition and pseudo-Lanchester formulation defined above. The fitted values of the parameters for each pseudo-Lanchester formulation are shown in Table 4.

Combat degradation represents an additional source of variability, which must be added to that already inherent in the structuring of an engagement into mini-battles under different sets of conditions. We have concluded that, even so, quite simple pseudo-Lanchester formulations may still have the potential to serve as useful attrition summary devices.

So far as the tested formulations are concerned, in the 'Power Law' the parameter $b3$ quite clearly reflects the altering balance of killing power as the characteristics of the parent attacker and defender populations are varied. However, the other two parameters are hardly responsive to these changes (although there is a minor tendency for the value of $b2$ to shift towards unity as the effectiveness of the defence declines). The 'Search with Overkill' parameters on the other hand are extremely responsive to these changes in assumptions. The value of the $a2$ parameter, and to a lesser extent

that of *a3*, shifts markedly as the effectiveness of the defending force declines. The implication would be that with increasingly ineffective defending forces the balance of attrition will depend less and less on the starting odds in each engagement. It is interesting to note that changes in the effectiveness of the attacking force have very little influence on the relative standing of the *a2* and *a3* parameters. As with the 'Power Law' *b3* parameter, the 'Search with Overkill' *a1* parameter appears faithfully to reflect the shifting balance of killing power between the two sides. Table 3 shows that, with one exception (the *x* dimension of *A3 vs D2*), the 'Search with Overkill' Law provides a better fit to the experimental results than does the 'Power' Law.

CRITERIA FOR DEFEAT

In this last section of this series of papers the emphasis will swing away from the frame of reference provided by Lanchester and Osipov. Lanchester had nothing directly to say about the mechanisms of victory or defeat. However, because the theory has been so conceptually appealing, and because its very essence is that of force-on-force and attrition, it has been influential in generating modeling doctrines couched in these terms. The approach in this section will therefore be somewhat different from that taken in other sections. It will be much more speculative, and there will be no attempt to link results directly to any pseudo-Lanchester formulation. Instead of summarising the main trends noted in quantitative analyses of trial results and battle records, the account of the evidence from these two sources will be more in the way of a discussion about the nature of defeat in the mobile land battle.

The Evidence from Trials and from Battle

Considerations at the Operational Level In a recent *MORS* paper concerned with manoeuvre warfare (Speight, Rowland & Keys, 1997) it was shown that there was practically no recent historical association between straightforward force ratio and the chances of operational success. This is hardly an isolated finding. Helmbold (1995 *et seq.*) in his *PHALANX* articles on 'Combat Analysis' has demonstrated this same point over an extended collection of historical battle records. We must clearly look elsewhere for the main causes or characteristics of defeat at this level.

In most historical battles casualty rates have been all that high. Scales (1995) in his summary of the data from 602 battles showed that the mean losses per day were some 4% of the mean initial strength for the attacker and about 6% for the defender. Nevertheless, there does appear to be a significant historical association between the relative attrition rates of the two sides and the chances of success. Thus, Helmbold (1961, 1964, 1995 *et seq.*; see also Hartley, 1991a, 1991b) has shown that, while the straightforward force ratio has had little effect, there has been a clear association between the '*V*' parameter and the chances of victory:

$$V = ln\{(x_0^2 - x^2)/(y_0^2 - y^2)\} - 2\ ln(x_0/y_0)$$

In crude terms what this association is indicating is that the likelihood of victory for one side has increased as the loss ratio has decreased when compared to the initial force ratio. But of themselves such empirical findings cannot elucidate the mechanisms which may produce a lowered relative casualty rate. Furthermore, since historical casualty rates have seldom been so high as to seem decisive of themselves, neither can it be absolutely certain why these rates link so clearly to operational success.

The manoeuvre warfare study already referred to (Rowland, Speight & Keys, 1996; Speight, Rowland & Keys, 1997) suggested one overwhelming characteristic of success at the operational level: that the integrity of the opponent's defensive line had been fatally compromised. This line could be compromised by successful outflanking manoeuvre or breakthrough, in which case the cost in casualties would most likely be low. If manoeuvre failed it could be produced less certainly by a continued process of attrition, probably at a greater cost in casualties. This paper is directed towards the tactical engagement. Accordingly, the emphasis for the moment will be on the translation of these operational considerations to the lower level.

Considerations at the Tactical Level. There is clear evidence at the tactical level that attrition *per se* has seldom been the cause of mission success or failure. Figure 4 is based on a sample of 113 German attacks on British positions from actions in Greece and North Africa. The mean number of weapon systems in the attacking force was 23.7. Excluding the 6 engagements in which all of the attacking force were casualties (but had not broken off prior to this), the figure shows the distribution of proportional losses where the attack had been aborted and where it had been pressed home. There is precious little distance between the two distributions. Clearly, something other than casualties had been the major determinant of the attacking commander's decision whether or not to proceed with his mission.

At the tactical level, as at the operational, manoeuvre has frequently been the key to success. In the British CHINESE EYE trials the most clear cut tactical victories for the attack occurred when the defender's position was compromised with scarcely a shot fired. Examples included a defensive deployment which failed to take account of a skilled and non-obvious line of advance, and another where extremely poor visibility severely impeded the chances of target acquisition. At the other extreme Rowland (1984) illustrates another CHINESE EYE scenario, where attacking force attrition was extremely heavy, but the few survivors still managed to break through at one decisive point in the defensive line. In all these cases the spatial integrity of the defence had clearly been compromised. The challenge is to find a simple and abstract modelling approach to represent the more usual situation where the causes and characteristics of defensive or attacking failure are not so cleat cut.

Combat Degradation, Collective Performance and the Chances of Defeat. Concomitants of defensive failure can include retreat or surrender of all or part of the defensive force. Parallel

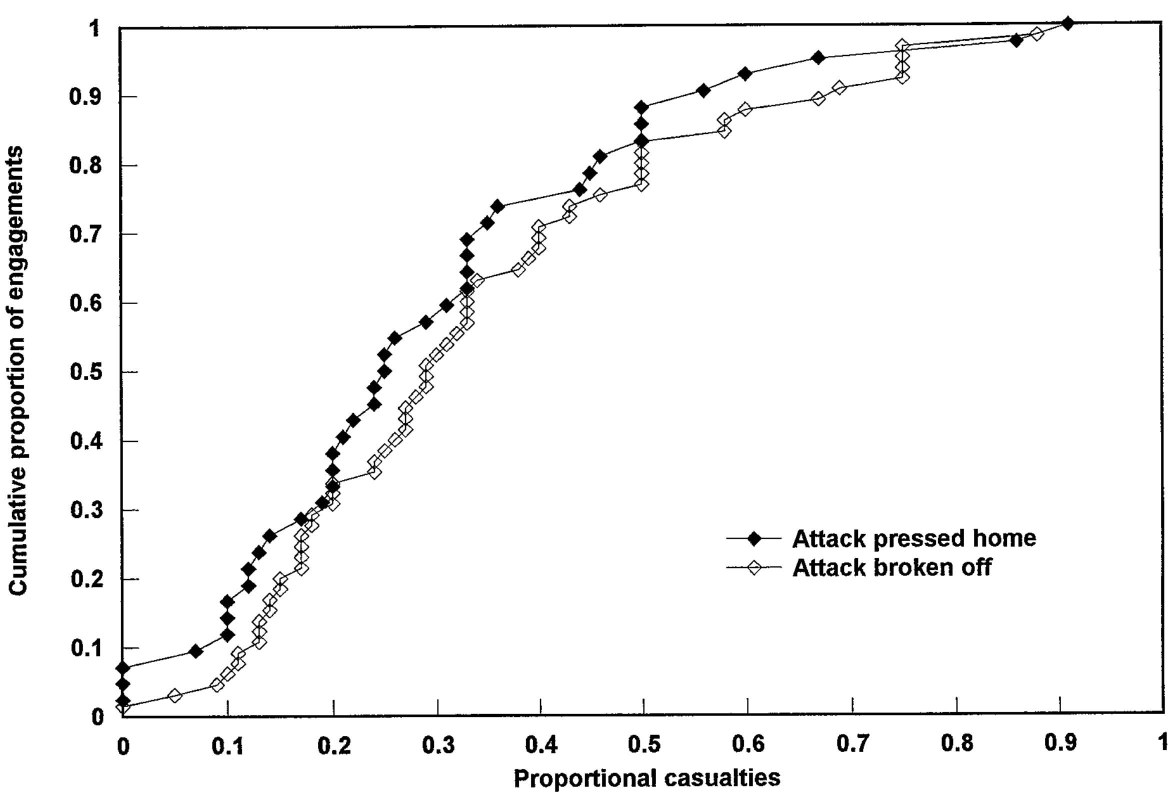

Figure 4. Proportional casualties in a sample of German World War II attacks on British positions in which the attacker broke off, or pressed home, the engagement.

studies of collective performance (not yet in the public domain) have shown a very significant association between the ability of an army to inflict casualties in the defence; the casualty level at which a force will surrender; and the expected rate of retreat as a function of attacker: defender force ratio. The relationship between the first index and the second appears to be linear, and that between the first and the last appears to be quadratic. The value of the last index does not appear to be particularly sensitive to the effectiveness of the attacking force. Naturally, there is appreciable random scatter about these empirical trends. Hartley's (1991b) extensive regression analysis investigation also shows that there is a positive association between victory and an index including '*V*' (casualty inflicting performance), advance rates and force effectiveness (which he links to nationality).

A Modelling Approach to the Determination of Defeat at the Tactical Level

In the modelling approach presented here it is assumed that the mission assigned to the attacking commander is couched in both geographical and military terms. The approach is based on the postulate that the necessary conditions for attack success are: that the attacking commander maintains an assessment that he has, or will have, an overwhelming strength advantage at the critical point; and that this condition does in fact obtain when he arrives at the latter. So long as he maintains this assessment he will press home his attack (in some cases even to the point of annihilation). At the time he arrives at a contrary assessment he will break off the attack.

In the CHINESE EYE trials, which have helped to guide the structure of the laboratory battle simulation, the defensive front averaged some 3 km in width and the attacking front some 1.5 km. For the purposes of the model the 'critical point' was designated as the half portion of the notional defensive line which coincided with the attack frontage. It was also assumed that, although the full defensive force could participate with equal probability in the mini-battles of which each engagement was composed, half were deployed on the critical portion of the defensive line. The other half, if they maintained their positions and the attack was successful, would be bypassed. Since lateral displacement along the defensive line is not truly represented in the model, half were assigned as 'key' defenders at the start of each battle run. This assignment was made at random, independently of the previously-sampled 'heroic' status of the weapon crew. (In practice it is entirely possible that the defending commander will have a shrewd impression as to the identity of the most reliable weapon crews, and will exercise skilled judgement in placing the latter at the point which turns out to be most critical for the defence.)

Breakthrough 'success' or 'failure' in each run was assessed in terms of an 'overwhelming strength advantage' at the 100m point. The threshold advantage criterion was that the total remaining attack weapons, whatever their 'heroic' status, exceeded 8 times the remaining 'key' defenders, excluding those in the 'inactive' category. The rationale for this was that, either objectively or in the putative attacking commander's assessment, it seems sensible to exclude from the military balance equation those weapons which are making absolutely no contribution to the battle. The chosen threshold factor of 8 was chosen arbitrarily, and is just one of the items which should be checked by further historical analysis.

Results

Tables 5 and 6 present some aggregated results for the same four experimental conditions which featured in Figures 2 and 3. Concentrating for the moment on statistical features of the 'probability of breakthrough' figures, it will be noted that there appears to be a stepped increase in probability as the numbers of attackers increase by a multiple of 8. This is a common feature of all such threshold schemes with small numbers. On practice there must be considerable uncertainty in assessments of numbers on the field of battle, let alone in decisions as to what may constitute an appropriate strength advantage. There may be some point, too, in weighting 'heroes' differently from the 'partially active'. However, no attempt has been made in this study to produce a finished methodology, and so it was thought best to show the results in raw form in order to expose the model's basic properties.

Table 5. Summary engagement statistics. Defender effectiveness level *D1*. Attacker effectiveness levels *A1* (left) and *A3* (right)

Attackers	Defenders (y_0)											
(x_0)	24	16	12	8	6	4	24	16	12	8	6	4
	Probability of breakthrough											
32	0.000	0.001	0.006	0.119	0.382	0.845	0.000	0.000	0.000	0.045	0.211	0.725
24	0.000	0.000	0.000	0.021	0.109	0.436	0.000	0.000	0.000	0.008	0.051	0.301
16	0.000	0.000	0.000	0.002	0.014	0.099	0.000	0.000	0.000	0.001	0.007	0.065
12	0.000	0.000	0.000	0.002	0.015	0.098	0.000	0.000	0.000	0.000	0.004	0.061
8	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.001	0.006
6	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.004
	Mean defenders surviving (whole sample)											
32	21.77	14.20	10.49	6.87	5.10	3.34	23.44	15.54	11.63	7.71	5.77	3.82
24	22.31	14.58	10.84	7.12	5.29	3.47	23.61	15.64	11.72	7.77	5.82	3.87
16	22.91	15.05	11.17	7.38	5.51	3.64	23.72	15.76	11.80	7.85	5.87	3.90
12	23.17	15.29	11.38	7.50	5.61	3.70	23.80	15.82	11.84	7.88	5.90	3.93
8	23.45	15.51	11.55	7.66	5.71	3.79	23.87	15.88	11.89	7.91	5.93	3.95
6	23.61	15.60	11.63	7.72	5.75	3.82	23.90	15.91	11.91	7.93	5.95	3.96
	Mean defenders surviving (breakthrough subset)											
32		10.00	8.50	5.77	4.55	3.22			11.50	7.30	5.53	3.76
24			8.50	5.91	4.47	3.12				7.26	5.49	3.73
16				6.38	4.43	3.02				7.25	5.53	3.69
12				6.91	4.68	3.23				8.00	5.64	3.80
8				8.00	5.00	3.28					5.67	3.79
6				6.00	4.00	3.36					6.00	3.75
	Mean attackers surviving (whole sample)											
32	23.40	26.01	27.46	28.83	29.63	30.40	23.13	25.78	27.19	28.67	29.45	30.28
24	16.08	18.36	19.68	21.02	21.75	22.44	15.84	18.23	19.47	20.84	21.62	22.33
16	9.04	10.99	12.10	13.26	13.92	14.59	8.96	10.94	11.97	13.23	13.87	14.52
12	5.79	7.37	8.42	9.48	10.08	10.68	5.82	7.44	8.37	9.46	9.99	10.63
8	2.96	4.13	4.89	5.79	6.28	6.82	2.97	4.14	4.91	5.80	6.28	6.75
6	1.69	2.64	3.26	3.99	4.44	4.90	1.74	2.63	3.25	4.00	4.41	4.87
	Mean attackers surviving (breakthrough subset)											
32		29.33	30.14	29.79	30.18	30.52			28.00	30.25	30.29	30.52
24			22.50	22.40	22.62	22.87				22.62	22.82	22.94
16				15.50	15.06	15.29				15.00	15.44	15.42
12				11.64	11.41	11.42				12.00	11.18	11.57
8				8.00	8.00	7.88					8.00	7.86
6				6.00	6.00	5.92					6.00	6.00

Discussion

What these results suggest, if the model and concepts do have some measure of combat validity, is that the ability to stand firm is far more a function of the resolve of the defensive force (and less so of the attacking force) than it is of attrition. Defender losses are not much greater when they are 'ineffective' than when they are 'effective', but there is a far higher probability that the defence will be broken through. The number of attackers who are likely to survive is indeed affected by the quality of the defence, but (as the German *vs.* British battle outcomes illustrated in Figure 4 show) there is precious little difference between the successful and unsuccessful subsets.

It is not pretended here that the scheme just put forward provides the analyst with all the manoeuvre battle modelling answers. The intention is to float ideas and concepts, not to produce definitive results. There are many challenges which have not been met, such as extending this partial methodology to cover

Table 6. Summary engagement statistics. Defender effectiveness level *D3*. Attacker effectiveness levels *A1* (left) and *A3* (right)

Attackers	Defenders (y_0)											
(x_0)	24	16	12	8	6	4	24	16	12	8	6	4
	Probability of breakthrough											
32	0.622	0.857	0.939	0.989	0.995	0.999	0.521	0.802	0.910	0.977	0.994	1.000
24	0.355	0.630	0.792	0.923	0.965	0.988	0.292	0.573	0.745	0.899	0.957	0.989
16	0.122	0.318	0.489	0.694	0.802	0.899	0.098	0.286	0.447	0.654	0.783	0.892
12	0.119	0.307	0.467	0.683	0.804	0.901	0.098	0.281	0.442	0.659	0.779	0.883
8	0.023	0.077	0.158	0.284	0.388	0.543	0.021	0.073	0.142	0.279	0.368	0.513
6	0.024	0.082	0.152	0.286	0.378	0.527	0.020	0.072	0.141	0.267	0.383	0.514
	Mean defenders surviving (whole sample)											
32	20.94	13.78	10.25	6.78	5.05	3.33	23.21	15.43	11.55	7.67	5.78	3.83
24	21.60	14.26	10.62	7.01	5.25	3.49	23.38	15.56	11.65	7.76	5.81	3.86
16	22.30	14.70	11.00	7.29	5.44	3.61	23.57	15.68	11.76	7.82	5.86	3.91
12	22.62	15.00	11.20	7.42	5.54	3.68	23.66	15.75	11.81	7.87	5.89	3.93
8	22.99	15.25	11.39	7.58	5.66	3.77	23.76	15.82	11.85	7.89	5.92	3.95
6	23.18	15.38	11.51	7.64	5.72	3.81	23.80	15.85	11.88	7.91	5.93	3.95
	Mean defenders surviving (breakthrough subset)											
32	20.70	13.70	10.22	6.77	5.04	3.33	23.12	15.40	11.54	7.67	5.77	3.83
24	21.29	14.14	10.54	6.99	5.24	3.49	23.28	15.52	11.63	7.75	5.80	3.86
16	22.03	14.50	10.88	7.22	5.40	3.59	23.42	15.62	11.73	7.81	5.85	3.90
12	22.25	14.82	11.12	7.36	5.50	3.66	23.56	15.69	11.78	7.85	5.88	3.92
8	22.59	15.04	11.23	7.51	5.60	3.72	23.62	15.77	11.81	7.86	5.90	3.94
6	22.96	15.22	11.36	7.55	5.67	3.77	23.75	15.80	11.86	7.90	5.91	3.94
	Mean attackers surviving (whole sample)											
32	30.65	31.10	31.33	31.55	31.65	31.77	30.56	31.05	31.26	31.52	31.62	31.74
24	22.72	23.13	23.33	23.58	23.67	23.77	22.65	23.12	23.33	23.54	23.65	23.78
16	14.79	15.20	15.40	15.59	15.71	15.80	14.75	15.18	15.36	15.59	15.69	15.79
12	10.90	11.25	11.44	11.62	11.73	11.80	10.87	11.22	11.43	11.61	11.71	11.80
8	6.98	7.32	7.50	7.66	7.74	7.83	7.01	7.30	7.47	7.67	7.73	7.81
6	5.09	5.38	5.52	5.67	5.76	5.83	5.09	5.36	5.53	5.68	5.76	5.83
	Mean attackers surviving (breakthrough subset)											
32	31.05	31.24	31.40	31.56	31.66	31.77	31.08	31.24	31.36	31.55	31.63	31.74
24	23.34	23.43	23.51	23.65	23.70	23.78	23.40	23.46	23.55	23.63	23.69	23.79
16	15.59	15.69	15.72	15.77	15.82	15.85	15.70	15.72	15.72	15.80	15.82	15.85
12	11.72	11.72	11.75	11.79	11.83	11.85	11.72	11.74	11.78	11.81	11.84	11.86
8	7.95	7.97	7.98	7.99	7.98	7.99	7.99	8.00	8.00	7.99	8.00	8.00
6	5.99	5.99	5.99	5.99	5.99	5.99	5.99	5.99	5.99	6.00	6.00	6.00

better the decision to abort a mission, as well as to represent the actions and consequences of mission failure. Nevertheless, this approach does unify some of the features noted in historical research. It suggests that there is a common ground to the ability to inflict casualties; the loss level at surrender; and the rate of retreat given the relative strength of the opposing force. Those forces which have a greater proportion not participating directly in the battle will inflict fewer casualties and will be broken through more frequently. The overrun remnants will then have to surrender or withdraw under the most hazardous circumstances. As individual units are broken through more often, so will the defending force have to retreat more rapidly if it is to maintain a cohesive defensive line.

CONCLUDING REMARKS

This series of papers began with Lanchester theory as an important thread, and so it seems

only right to return with a general appraisal at its end. It is hard to disagree with Bowen & McNaught (1996) that a simple theory may have great value as a conceptual tool and as an aid to understanding, even when embedded in it are some distortions and over-simplifications of the complexities of modern warfare. This paper and its predecessor have shown that, even when care is taken to portray just some of these complexities which violate the basic Lanchester assumptions, this formulation may still have value as a summarising device. Above all, scientific enquiry and research has in general been most productive when prodded, provoked and guided by even the most provisional and simple hypothesis. The wealth of military OR research papers stimulated by Lanchester theory is testimony to this assertion, and his continuing place in OR history is assured. However, the achievements due to Lanchester theory have perhaps been gained at a price, by deflecting attention away from the structure of war, especially spatial structure and that of military intent. In the Lanchester formulation it is as though the opposing forces have been stirred into some inert mixing solution and left to interact as mutually antagonistic species. The side wins which first eliminates the other, or which reduces the other to a level where it no longer constitutes a threat. Perhaps the time has come to shift the emphasis a little away from the important dimension of attrition towards those of the spatial and human dynamics of war.

These papers have been written very much in the spirit of Lanchester: that an imperfect and provisional theory is a good deal better than no working hypothesis at all. For the authors, at least, this exercise has highlighted important gaps in our knowledge: for instance, a systematic description of the process by which mini-battles form, or of the rules governing the detection of multiple targets. But, most of all, our modelling of the mobile land battle would be improved by a fuller understanding of the human and social dimensions of combat behaviour. Improving the representation of these factors, well beyond the modest confines of these papers, seems a worthwhile aim for the military OR community as a whole. We then might be seen to be addressing the topics which, history suggests, have been the major drivers of performance on the battlefield.

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Environmental Factors in Amphibious Operations

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INTRODUCTION

This article provides an overview of an effort to quantify the impact of environmental factors on amphibious operations. Two primary objectives of the analysis are summarized:

- Develop a methodology to rank-order environmental factors in proportion to their impact on warfare effectiveness.
- Demonstrate the operational impact of the environment using methods and measures employed in high-level studies as part of the Navy assessment and budgeting process.

The rank-ordering methodology provides a big-picture operational perspective to researchers in environmental science, modeling, and data collection. The methodology relates individual environmental initiatives to anticipated tactical applications and provides a sense of prioritization from the operator's point of view.

The high-level impact analysis puts environmental research and products on the same footing as traditional research, development, and procurement of combat systems from the perspective of program planners and decision-makers. Such analysis highlights the extent to which operational assessment analysis depends on the environmental context and allows environmental programs and products to be traded off against sensors, weapons, and platforms.

This analysis promotes technical communications among environmental and operational analysts.

Amphibious operations were selected as the warfare context for methodology development. The following sections discuss amphibious operations, environmental factors, the weighting and ranking methodology used, and an example of a high-level operational impact of the environment. Many details, especially those describing amphibious systems and environmental factors, have been omitted from this overview. A complete discussion can be found in [Del Balzo, Vodola, and Beveridge] together with additional sensitivities and backup data.

AMPHIBIOUS OPERATIONS

In the analysis, amphibious warfare (AMW) was broken down and structured as a hierarchy. First, amphibious operations were partitioned into eight subordinate operational components. Each operational component was further broken down into a variable number of key platforms. The resulting framework is like a pyramid with three levels. At the top is amphibious warfare. The second level is made up of the operational components which, in turn, are broken down into constituent platforms forming the third level.

The eight operational components are shown in Figure 1, which also indicates how these components are typically executed in a coordinated, time-phased manner. In the more general warfighting context, one would add battlespace dominance (anti-air warfare (AAW), antisubmarine (ASW), anti-surface ship warfare (ASUW), etc.), other forms of power projection such as strike, and supporting tasks like logistics and resupply. This analysis focused on joint littoral operations and, further, assumed successful dominance of the battlespace.

Figure 2 is a listing of the eight operational components and the platforms associated with each component. The term platform is used loosely to include major combat system elements and other resources that contribute to the execution and success of an operational component.

At this point a hierarchy has been structured in the style of Figure 3. The ship-to-objective component is partitioned into supporting platforms by way of illustration. The breakdown of each of the seven other operational components, specified in Figure 2, is not shown in Figure 3 to reduce its complexity.

ENVIRONMENTAL FACTORS

The development and selection of environmental factors for this analysis had to be broad enough in scope to encompass all features of the environmental setting that are likely to influence amphibious operations. At the same time, it had to be focused sufficiently to permit analysts to relate factors to one another and to specific amphibious warfare (AMW) components. If the breakdown were too refined and scientific, the analyst and operations expert would be burdened with the need to aggregate factors into environmental processes whose impacts were understood only to varying degrees. If the breakdown were too coarse and subjective, scientists would have difficulty discerning specific relationships and understanding how databases and process models map to operations.

After several iterations, the set of environmental factors was categorized into 36

OR METHODOLOGY
Decision Analysis
APPLICATION AREA
Land and Expeditionary Warfare
Modeling, Simulation and Gaming

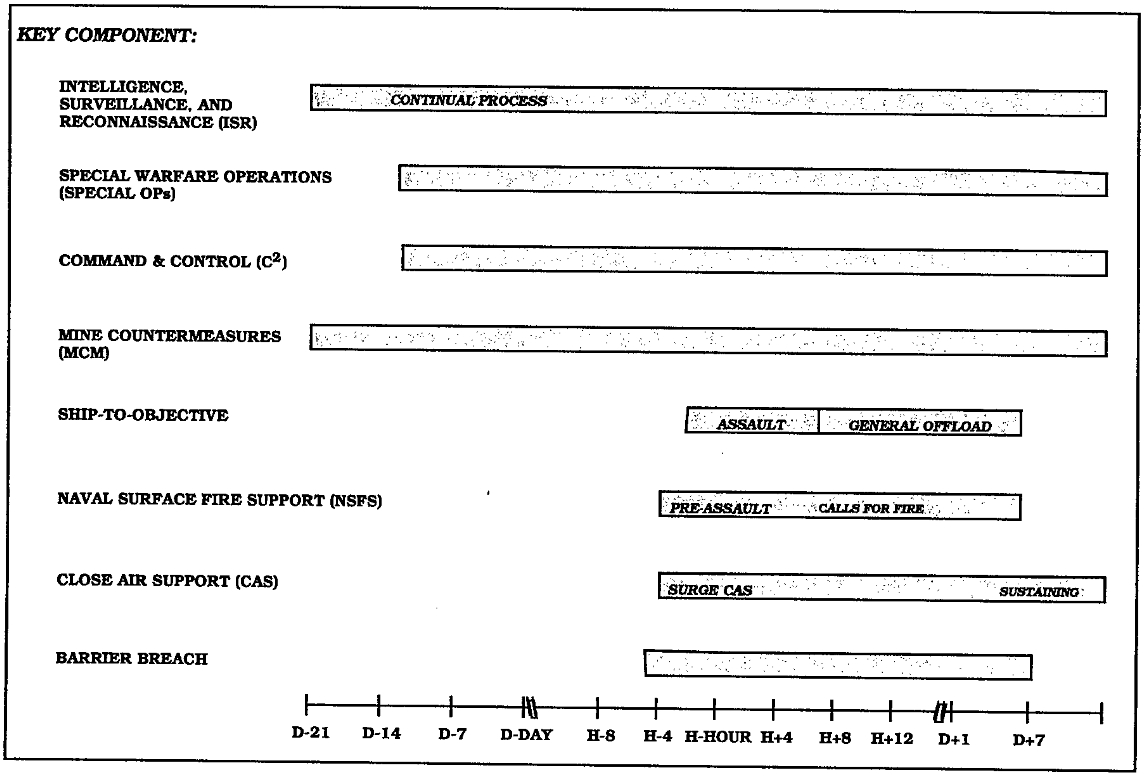

Figure 1. AMW Components and Flow in Operational Maneuver from the Sea

specific environmental factors distributed into six categories, as shown in Figure 4.

Perhaps the most important criterion for inclusion is that the environmental factor have an intuitive meaning to both operational experts and scientific analysts. The potential to impact the mobility or general combat worth of a platform, its sensors, or its combat subsystems had to be relatively transparent.

The hierarchical breakdown of Figure 5 is completed by inserting these factors at the base of the operational pyramid shown in earlier Figure 3. Only the ship-to-objective component has been decomposed into its constituents. The 36 individual environmental factors are represented by the six general categories. In the actual display, all 36 environmental terms lie under every platform-level unit in the structure.

ENVIRONMENTAL FACTOR EVALUATION

General Case

The objective of the qualitative analysis was to produce a rank-ordered list of environmental factors where each factor is weighted by its impact on overall amphibious operations. A decision-theoretic approach was adopted. These techniques are used commonly by operations research analysts and are valued for their efficiency, relevance, and ability to exploit experience while promoting consensus among diverse experts.

Amphibious operations have been depicted in Figure 5 as being composed of eight operational components of which the ship-to-objective component is executed through the employment of six platform types that are required to operate under environmental conditions typified in six categories. To establish the importance of an individual environmental factor on amphibious operations, it was necessary first to determine its importance relative to the operational components and their platforms. This was done by working down the nodes of the pyramid in a sequential manner and ranking the perceived importance of the set of elements below and connected to that node. For example, if the ship-to-objective component were perceived to be the most important of all AMW components, it would be assigned a rel-

COMPONENTS and PLATFORMS		
CAS HELICOPTERS ALL WEATHER ATTACK DAY/VFR ATTACK FAC	ISR SSN P-3 EP-3/ES-3 TARPS UAV SEAL TEAM NATIONAL ASSETS	SHIP-TO-OBJECTIVE AMPHIBIOUS SHIPS LCAC AAV/AAAV CAUSEWAYS LCU/LCM HELICOPTERS
BARRIER BREACH SEAL TEAM AAV/AAAV LCAC COMBAT ENGINEER STRIKE AIRCRAFT NSFS	MCM HELICOPTERS MCM/MHC MINE LAYING AIRCRAFT SSN	C^2 CV/LCC SSN CG/DDG AMPHIBIOUS MCM/MHC E-2 STRIKE AIRCRAFT HELICOPTERS LCAC AAV/AAAV INFANTRY ARMOR ARTILLERY COMBAT ENGINEERS FAC
NSFS GUNSHIPS UAV ANGLICO CRUISE MISSILE SHIP	SPECIAL OPERATIONS SSN HELICOPTERS PARACHUTE SEAL TEAM SDV PC/RRC	

Figure 2. Breakdown of Operational Components into Platforms

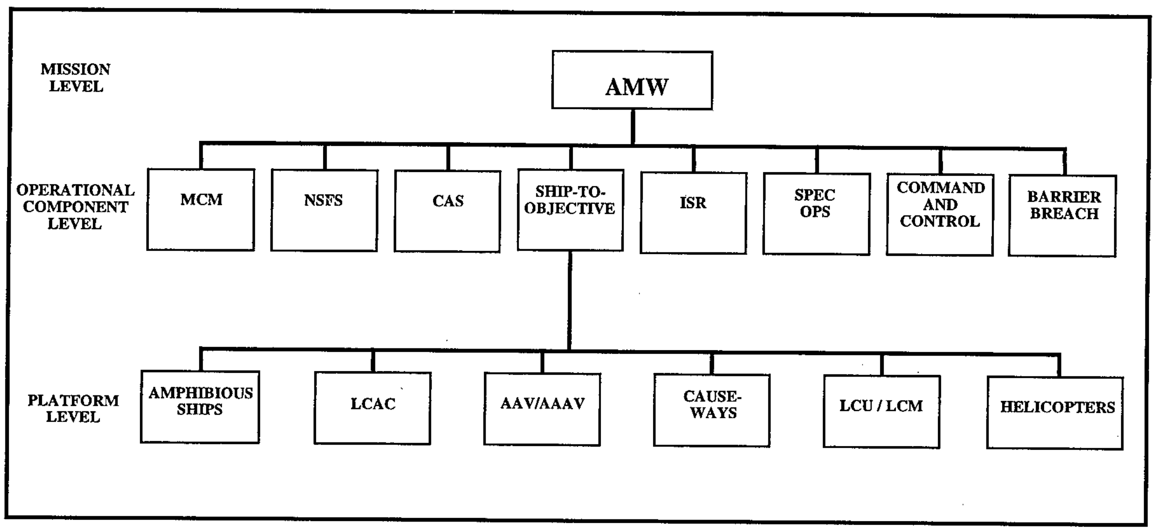

Figure 3. Hierarchical Breakdown of Amphibious Operational and Ship-to-Objective Component

ative rank of 1 with less important components ranked 2 or 3, based on their perceived importance. The process was then extended to each platform within a component. Thus, if the LCAC were considered to be the most important platform supporting the ship-to-objective component, it would be assigned rank of 1. Finally each environmental factor was ranked with respect to its importance to the operation of each platform. So if sea state were deemed to have the greatest impact on an LCAC in the ship-to-objective component, then it would be assigned a ranking of 1. Ties were allowed when impacts and contributions were approximately equivalent.

The ranks in the amphibious operations hierarchy were then converted to weights. The philosophy was that if A dominated B by one unit of rank, then the relative weight of A would be twice that of B. Our ranking scheme

ATMOSPHERIC	ANTHROPOGENIC
AMBIENT LIGHT CLOUDS PRECIPITATION VISIBILITY PARTICULATE MATTER AIR TEMP/HUMID/PRESSURE ELECTROMAGNETIC CONDITIONS WIND SPEED & DIRECTION REFRACTIVE INDEX SUN GLINT/GLARE	OBSTRUCTIONS/SURFACE CLUTTER BOTTOM CLUTTER NOISE **HYDROGRAPHY** TOPOGRAPHY (LAND, WATER) DRAINAGE BEACH CHARACTERISTICS DEPTH RANGE
BIOLOGIC	**GEOPHYSICAL/MAGNETIC**
REEFS, KELP, LAND VEGETATION SCATTERERS (OPTICAL, ACOUSTIC) AMBIENT NOISE BIOLUMINESCENCE BIOFOULING	SEDIMENT COMPOSITION BOTTOM ROUGHNESS CLUTTER (ACOUSTIC & MAGNETIC) SEDIMENT GASES SEDIMENT STRENGTH & STABILITY GEOACOUSTIC PROPERTIES
OCEANOGRAPHIC	
SURF CONDITIONS SEA/STATE/SWELL & DIRECTION TIDES OPTICAL PROPERTIES (TURBIDITY/VISIBILITY CURRENTS (LITTORAL, OCEAN) SALINITY/CONDUCTIVITY WATER TEMPERATURE BUBBLES	

Figure 4. Environmental Factors by Category

used ranks 1, 2, and 3 so the associated relative weights were 4, 2, and 1, respectively. An element making no contribution remained unranked and carried no weight. Thus at the platform level in the above example, if the LCAC were ranked 1 relatively to an AAV that was ranked 2, the LCAC and AAV would be assigned relative weights of 4 and 2, respectively. In this manner, the ranks of every operational component, platform, and environmental factor were converted to relative weights.

Figure 6 is a copy of Figure 3 showing the relative weights. It was the consensus that three operational components—MCM, ship-to-objective, and barrier breach—were significantly more critical to AMW mission success than the others. CAS, ISR, and C^2 were of secondary importance, and those remaining played a tertiary role. Most of the platforms composing the ship-to-objective component were equally important, with the exception of the older, slower LCU/LCM and causeways that play a specialized role in later phases of some amphibious scenarios. The weights assigned to environmental factors are not shown. The most critical factors with respect to the LCAC were sea conditions (sea state and surf) and visibility. Weather related factors impacted helicopters, and AAVs were affected by a combination of sea and weather factors.

A complete listing of weight assignments can be found in [Del Balzo, Vodola, and Beveridge].

The approach of the study team was to judge a component to be most critical if it contributed significantly to overall mission success in most reasonably imaginable regions of tactical importance under a broad range of realistic threat, operational, and environmental contexts. The same philosophy could be phrased from a negative perspective: the most important components are those whose failure is liable to result in overall failure of the amphibious mission under most realistic circumstances. This approach of declaring "stoppers" to be most critical elements among peers circumvented the problem of situation dependence and forced the contributing analyst to remain flexible and general when integrating professional experience. Participants in this study had

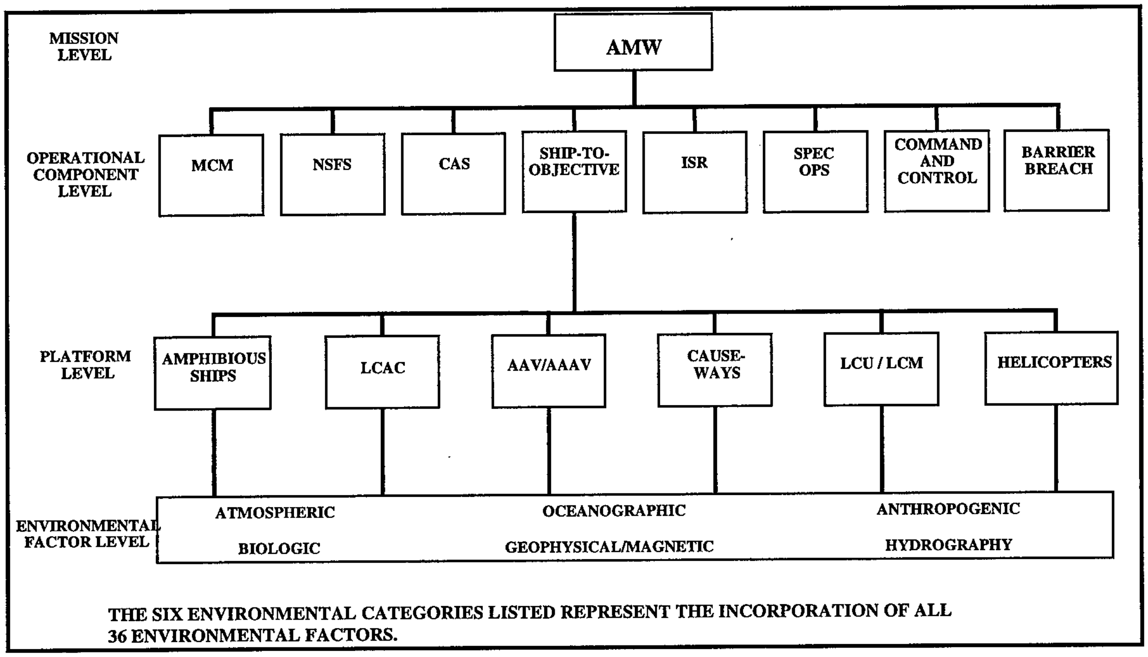

Figure 5. Hierarchical Breakdown from Operational Components to Environmental Factors

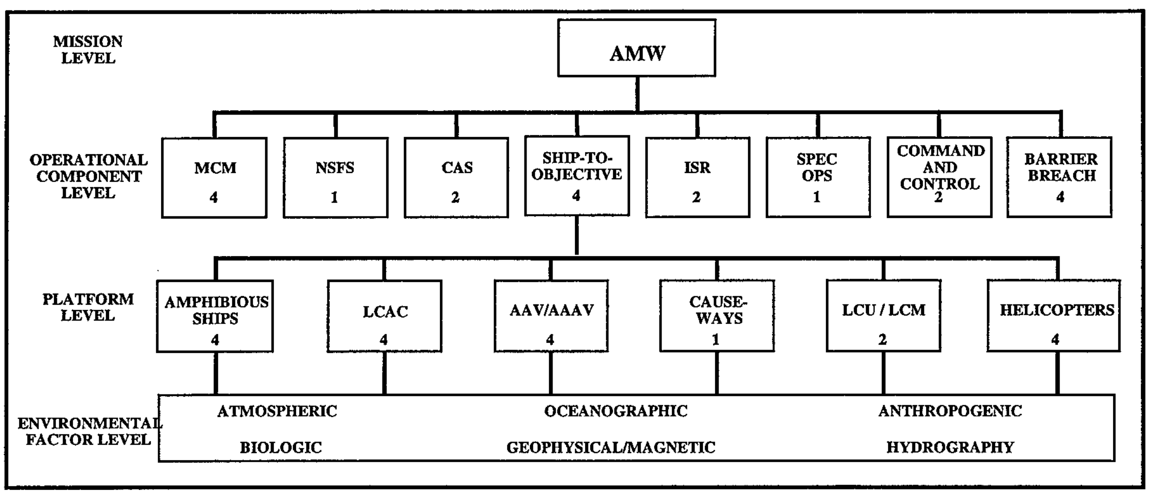

Figure 6. Hierarchical Breakdown and Weights from Operational Components to Platforms

decades of operational amphibious experience, as well as experience performing high-level operational assessments across a variety of diverse defense planning scenarios.

The weighted data were normalized and integrated to produce a rank-ordered list of environmental factors. The weights on the nodes directly under, and connected to, any given node are scaled to sum to unity. Thus, the weights of the eight operational components under the uppermost AMW node were scaled and the normalization process proceeded downwards to each node in the hierarchy. Partial products of the normalized weights were formed along each path in the tree. For example, the AMW—Ship-to-Objective—LCU/LCM—Electromagnetic Conditions path was weighted 4-2-1 and resulted in a normalized

path weight of 0.018. In this methodology, each path began with AMW, proceeded downward through an operational component and platform, and terminated with an environmental factor. The sum of the path weights over the entire hierarchy was unity because of the normalization. The relative importance of each environmental factor was the sum of the weights of all paths terminating in that factor. Thus, "visibility" accumulated importance because of its quantified impact on LCAC performance in the ship-to-objective component, on ANGLICO operations in the NSFS component, and so forth across all platforms participating in all operational components of AMW.

The integration resulted in the ranked list of environmental factors shown in Figure 7. The aggregate weights are shown next to each factor, and they are sorted in descending rank order. It would be proper to interpret these results as saying (among other things) that when considering general amphibious operations as a whole, visibility is the single most critical feature of the environment. It would be improper to conclude that tides, which are preceded by over a dozen more significant factors,

ENVIRONMENTAL FACTOR	WEIGHT	CUMULATIVE WEIGHT
VISIBILITY	0.083	0.08
TOPOGRAPHY (LAND, WATER)	0.073	0.16
REEFS, KELP, LAND VEGETATION	0.068	0.22
PRECIPITATION	0.067	0.29
AMBIENT LIGHT	0.057	0.35
CLOUDS	0.056	0.40
WIND SPEED & DIRECTION	0.054	0.46
SEA STATE/SWELL & DIRECTION	0.041	0.50
OBSTRUCTIONS/SURFACE CLUTTER	0.041	0.54
PARTICULATE MATTER	0.038	0.58
SUN GLINT/GLARE	0.037	0.62
AIR TEMP/HUMID/PRESS	0.037	0.65
ELECTROMAGNETIC CONDITIONS	0.027	0.68
TIDES	0.027	0.71
DEPTH RANGE	0.027	0.73
CURRENTS (LITTORAL, OCEAN)	0.027	0.76
SURF CONDITIONS	0.025	0.79
BEACH CHARACTERISTICS	0.024	0.81
BOTTOM CLUTTER	0.024	0.83
NOISE	0.021	0.86
REFRACTIVE INDEX	0.016	0.87
DRAINAGE	0.015	0.89
OPTICAL PROPERTIES (TURBIDITY / VISIBILITY)	0.013	0.90
SCATTERERS (OPTICAL, ACOUSTIC)	0.012	0.91
CLUTTER (ACOUSTIC & MAGNETIC)	0.012	0.92
BIOLUMINESCENCE	0.011	0.93
BOTTOM ROUGHNESS	0.010	0.94
WATER TEMPERATURE	0.010	0.96
SEDIMENT STRENGTH & STABILITY	0.009	0.96
SEDIMENT COMPOSITION	0.008	0.97
SALINITY/CONDUCTIVITY	0.008	0.98
AMBIENT NOISE	0.007	0.99
GEOACOUSTIC PROPERTIES	0.005	0.99
BUBBLES	0.004	1.00
BIOFOULING	0.003	1.00
SEDIMENT GASES	0.000	1.00

Figure 7. Ranked List of Weighted Environment Factors

could not influence or impair mission success. It is simply the case that features like visibility, topography, and ambient light are, on average, more likely to affect some critical phase of amphibious operations than are tides, turbidity, and sediment composition.

One can make several observations from the quantification and ranking process:

- 50% of the outcome of amphibious operations is driven by the eight most critical factors, and approximately two-thirds of the factors (23) account for 90% of mission effectiveness.
- From a mission planning perspective, one might view this list as a prioritized checklist for data gathering. This is the order in which planners must feel that knowledge and control within the environment have been achieved. This order indicates the relative marginal return for the gathering of additional information. Of course, this particular list is generic and would likely change if more details of a scenario were specified.
- The quantification process is traceable. That is, if one wanted more information on how visibility bubbled to the top of the list, one could examine the tree structure to see, in priority order, the specific platforms and mission roles that elevated visibility. This should agree with one's intuition. If not, one could examine those factors in the neighborhood of visibility to detect, refine, or correct the imbalance.
- The methodology supports "what if" analysis very efficiently. In general, one can parameterize the analysis from two perspectives: (1) vary the weight(s) assigned to one or more nodes of the tree structure, and examine the extent to which the ranking changes; (2) hypothesize a change in order, and discover what change in operational concept and relative impacts would result in the new order. For example, what would it take to move "precipitation" from number 4 to number 2?

One would expect that the weights assigned to the eight operational components could drive the final ranking. Considerable insight can be gleaned by examining extreme weighting schemes. That is, what if each component was the only contributor to the mission or was so dominant that the contributions of others was negligible? An overview of that sensitivity is shown in Figure 8 where only the top five factors are listed, in rank-order, for each of the eight components. Of particular interest are the factors like visibility, which show up in all or nearly all components, and factors like bottom clutter, which affect only one or a few. Several observations, all intuitive, can be developed from this presentation:

- A factor might be the most critical factor for the most critical component and still not make it to the highest portion of the integrated list. Bottom clutter for MCM is such an example.
- Some factors, such as clouds, may be high for many components but still be overtaken and omitted from the top of the integrated list. Similarly, a factor like vegetation may be high on the integrated list but not appear high among the components.
- Another phenomenon, not exhibited clearly in this example, is that a factor that has a moderate impact across several components of intermediate weight may float higher on the integrated list than it appears for any individual component. In fact, it was observed that if one restricted one's attention to the most critical factors for the most important platforms for the components of highest priority, the aggregate list would change measurably.

Application to Korean Theaters

So far the rankings have been independent of specific assumptions regarding threat, geographic region, and other scenario details. Although great care was taken to avoid familiar scenarios, there was great curiosity about the relative sensitivity of the structure and weights to such assumptions. The team performing this analysis had participated in detailed operations analysis of the Korean theater for several cycles of the POM assessment process. NRL environmental assessment guides and summaries were available for consultation. Two concepts of operations were conceived: one for the Sea of Japan approach from the East and a second for the Yellow Sea littoral to the West. The season was winter, consistent with analysis previously performed.

Figure 9 is a map of the area with a few distinguishing environmental features common to the region, as well as some that are unique to each side.

CAS	SPEC OPS
Visibility **Reefs, Kelp, Land Vegetation** **Topography (land, water)** **Precipitation** Clouds	**Reefs, Kelp, Land Vegetation** **Topography (land, water)** **Visibility** Clouds Noise
SHIP-TO-OBJECTIVE	**ISR**
Visibility Wind Speed & Direction **Topography (land, water)** **Reefs, Kelp, Land Vegetation** Sea State/Swell & Direction	**Visibility** **Precipitation** Clouds **Topography (land, water)** **Ambient Light**
MIW/MCM	**BARRIER BREACH**
Bottom Clutter **Reefs, Kelp, Land Vegetation** **Visibility** Wind Speed & Direction Sea State/Swell & Direction	**Visibility** **Topography (land, water)** **Reefs, Kelp, Land Vegetation** **Precipitation** **Ambient Light**
NSFS	**CMND & CONT**
Reefs, Kelp, Land Vegetation **Visibility** **Ambient Light** Clouds **Precipitation**	**Precipitation** **Topography (land, water)** **Visibility** Electromagnetic Conditions Clouds
Factors in bold are among the top 5 in the integrated list	

Figure 8. Top 5 Environmental Factors Within Components

Analysts factored these details into their weighting of platform performance and operational components, producing the ranked list of factors in Figure 10. Only the top five environmental factors are shown for each of the three most significant components as well as for the integration across components. As might be expected, these lists differ somewhat from one another and from the generic ranked list shown earlier in Figure 8. One new trend that was observed in this application was that certain features of the environment (e.g., ambient light, topography, vegetation, and weather-related factors) are so ubiquitous and so critical that they will likely rise to the top of the list in spite of other remarkable features. This is intuitive: features whose effects are pervasive throughout amphibious operations will dominate in most operational contexts.

OPERATIONS ANALYSIS

The amphibious phase is one of many operational situations that make up the campaign analysis and excursions for the POM assessment process. Detailed engineering analysis was underway at the same time that the ranking methodology was being applied. The details of that process and analysis were beyond the scope of this study, but basic scenario, approach, and results are relevant and easily described.

The first amphibious operation in the scenario is a short raid. The operation takes place nearly 4 weeks into the campaign when battlespace dominance has been achieved. Figure 11 is a diagram of the general operation.

The objective of the raid is to demonstrate the capacity to project power ashore at any time

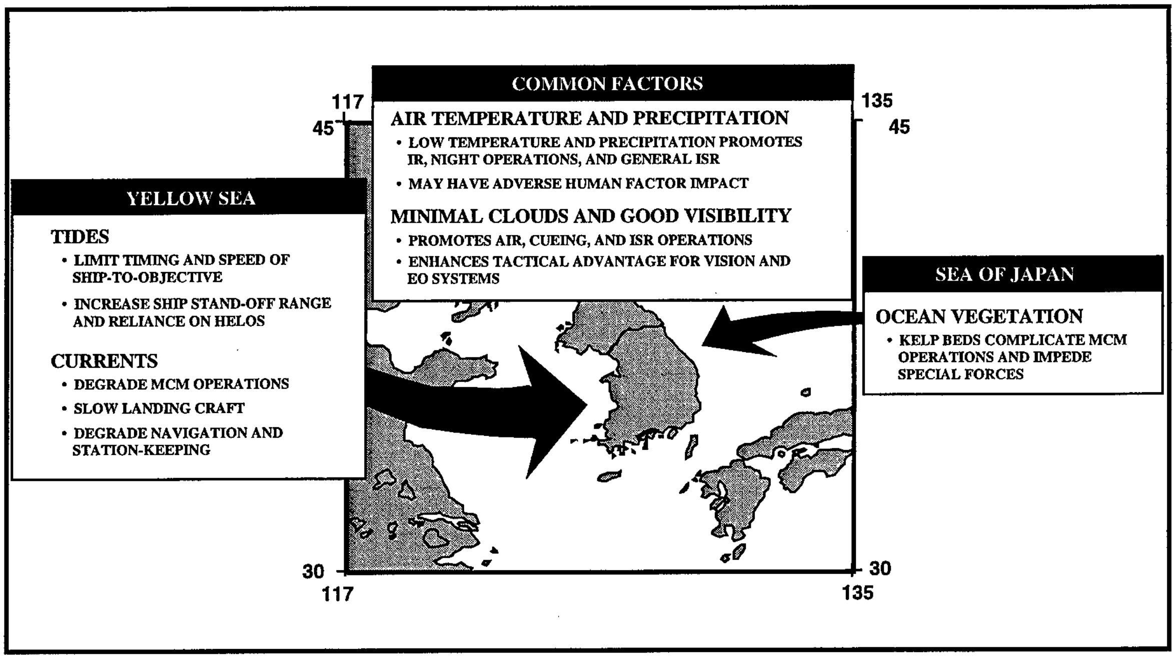

Figure 9. Critical Environmental Features in the Korean Theater (Winter)

TOTAL OVER ALL COMPONENTS	
YELLOW SEA	*SEA OF JAPAN*
Topography (land, water)	Topography (land, water)
Ambient Light	Reefs, Kelp, Land Vegetation
Air Temp/Humid/Press	Ambient Light
Tides	Wind Speed & Direction
Sun Glint/Glare	Air Temp/Humid/Press

SHIP-TO-OBJECTIVE	
YELLOW SEA	*SEA OF JAPAN*
Ambient Light	Ambient Light
Tides	Obstructions/Surface Clutter
Currents (littoral, ocean)	Topography (land, water)
Obstructions/Surface Clutter	Sea State/Swell & Direction
Beach Characteristics	Air Temp/Humid/Press

MIW / MCM	
YELLOW SEA	*SEA OF JAPAN*
Sediment Composition	Sediment Composition
Tides	Wind Speed & Direction
Currents (littoral, ocean)	Reefs, Kelp, Land Vegetation
Bottom Roughness	Air Temp/Humid/Press
Topography (land, water)	Topography (land, water)

BARRIER BREACH	
YELLOW SEA	*SEA OF JAPAN*
Topography (land, water)	Reefs, Kelp, Land Vegetation
Bottom Clutter	Topography (land, water)
Tides	Obstructions/Surface Clutter
Obstructions/Surface Clutter	Beach Characteristics
Beach Characteristics	Air Temp/Humid/Press

Figure 10. Top Five Factors for Critical AMW Operational Components

and place of our choosing. The tactical objectives are to destroy the submarine pens, destroy any weapons that are a threat to shipping, draw enemy forces from other strategic areas, and minimize blue casualties.

These operations are further broken down into significant events and tasks as indicated in Figure 12. The landing force is broken into packages that are deployed in coordinated waves to beaches and air landing sites. The order and timing of deployment are critical because these packages are mutually supportive. In general, each package improves survivability and mobility of forces that debark subsequently. Two analysis cases were investigated: a baseline, assuming benign environment conditions, and an excursion, assuming adverse conditions.

The results of the landing are summarized in Figure 13, which shows the buildup of combat forces ashore over time. To quantify the combat power of diverse forces using a common scale, a numerical value is assigned to each combat resource in proportion to its rela-

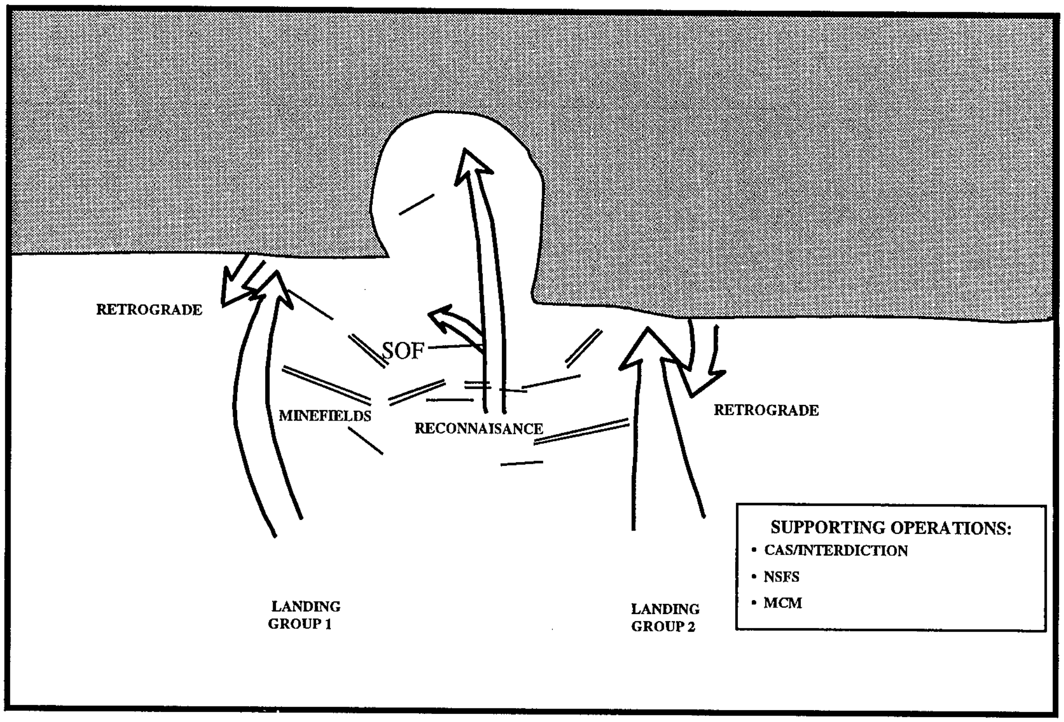

Figure 11. Ship-to-Objective Operations

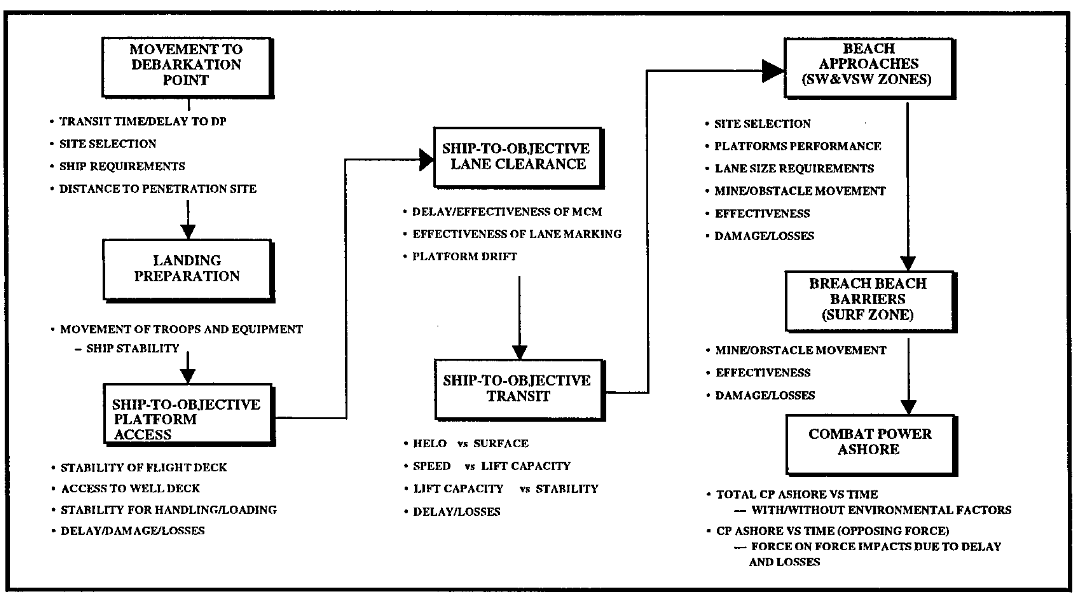

Figure 12. Combat Power Ashore During Ship-to-Objective Phase

tive combat value. Predictions and analyses of amphibious landings usually display combat power ashore as a key measure of mission success. This presentation shows combat power ashore for the entire operation which includes the retrograde phase when forces disengage

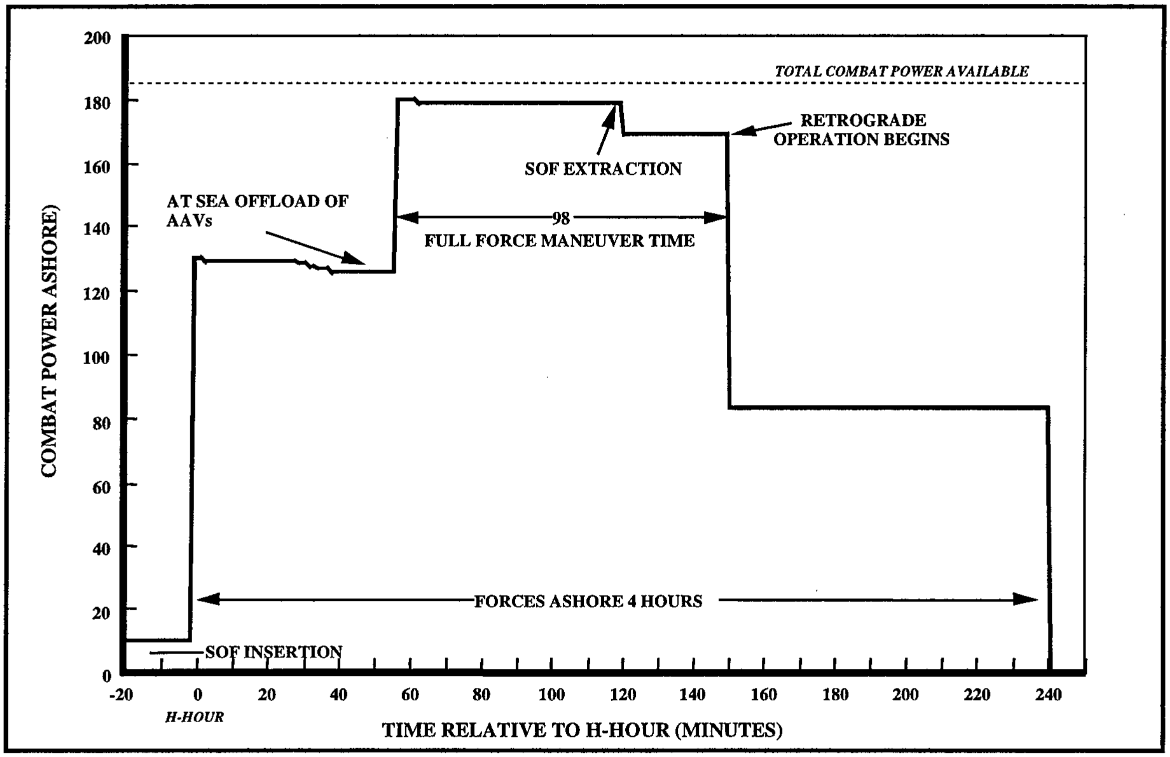

Figure 13. Raid Operations in a Benign Environment

and return to the ships. Under ideal circumstances, forces would be sized and transported as a single unit and the resulting display would be a simple rectangular function whose height represents the planned ground force requirement and whose width represents the amount of maneuvering time allocated to ground operations. Variances from the ideal rectangle represent undesirable but realistic degradations due to phased landings, transit delays, neutralization of obstacles and mines, and attrition. Split forces are more vulnerable, and every effort is made to minimize the separation of forces and to provide sufficient protection.

Performance under nominal baseline conditions is good. There is a lead time before all forces are brought ashore, followed by nearly 2 hours of ground operations, and an orderly retrograde. There is very little attrition and all components, from special forces to tanks, arrive on time in the desired number.

The distribution of sea state and wave heights, made available by using the Navy-standard surf model and climatology indicated that wave heights exceed 5 feet about 25% of the time. The results of executing the same concept of operations under high quartile surf conditions are shown in Figure 14. There is a substantial reduction on the ability to deliver combat power ashore, as well as higher attrition and increased vulnerability to the reduced forces. Some critical operations cannot be carried out.

The key operational impacts are:

- There are no SEAL and recon platform insertions due to rigid rubber boat limitations.
- There are only two littoral penetration sites vice four.
- There is a slower buildup of combat power ashore due to reduced speed of LCAC.
- In the baseline case, AAVs are offloaded from LCACs 4,000 yards at sea and they transit to the beach (20 minutes). In the excursion, AAVs cannot be offloaded in rough seas so they are delivered to shore, extending LCAC cycle times.
- Additional LCAC would be required to lift LAVs to beach.

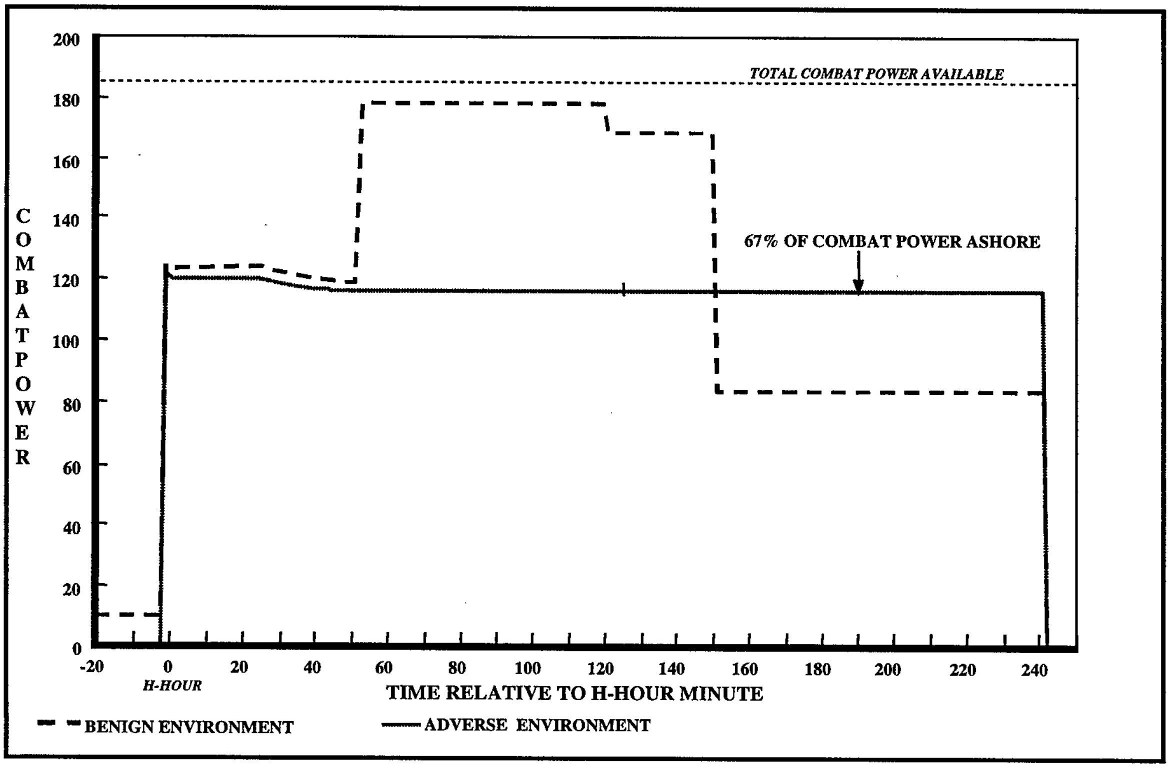

Figure 14. Raid Operations in an Adverse Environment

- Fewer forces are ashore because of cargo capacity limitations.
- There is less maneuver time available to accomplish mission and return to beach for the retrograde phase.
- Retrograde is an even higher risk operation because of reduced speeds and capacities of platforms.

This situation is untenable. Marines would not be asked to execute such a concept of operations under the conditions hypothesized. If warning about such conditions were available, forces would wait for more favorable conditions, develop an alternate operational plan, or abort the mission. This loss of options could be critical in a highly coordinated, tightly orchestrated campaign.

These operational vignettes are valuable because they show that the impact of environmental factors on mission success can be quantified using the approach and analysis tools of programmatic decision-makers. The enabling/disabling features of the environment are measured on the same scale as threat excursions, force level and force mix sensitivities, and other traditional investigations of program improvements and tactical developments.

CONCLUSIONS

This two-pronged approach to the quantification of environmental impacts on amphibious operations was enlightening and it produced valuable products. The relatively subjective application of decision theory to create weights and an ultimate ranking is a useful survey tool. Professionals are able to structure and examine the entire operational problem in spite of its complexity and myriad of environmental interfaces. One is less likely to overlook environmental effects because the process is too complicated and engineering tools are not readily applicable. The process also invites meaningful participation by experts with diverse experience and skills. Operational experience, environmental science, and analytical skills are integrated in a balanced fashion. This synergism is often lost in rigid engineering studies in which operators, scientists, and mod-

elers compete rather than cooperate. The process promotes an open, end-to-end investigation of all facets of this complex problem, yet results in a very focused list of environmental factors in rank order.

The operations and engineering analysis is the more scientific product of the study and the interface to high-level decision-makers. Impacts on mission success, as evidenced in high-level measures of success, are couched in the language and format by which programmatic decision-makers trade off and communicate the strengths and weaknesses of alternatives. Such analysis lifts scientific research and modeling beyond the sphere of scientists and engineers by enabling operators and decision-makers to visualize impacts in situations they find most critical and realistic. The operational Navy and Marine Corps forces are the ultimate customer for environmental data, research, and applications.

The two processes are actually branches taken from a common analysis framework. They share the need for hierarchical structure and elaboration of interfaces. Both require measures of effectiveness to serve as evaluation criteria and to integrate analysis performed at lower levels. One might regard weights as tentative proxies for performance estimates that take longer to develop and compute. The weighting methodology gives the analyst an opportunity to exercise the process, examine issues, and establish priorities that focus more detailed scientific and engineering studies.

ACKNOWLEDGEMENT

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Depot-Level Maintenance Planning for Marine Corps Ground Equipment

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ABSTRACT

Successfully maintaining a large, diverse fleet of tactical ground equipment for the U.S. Marine Corps requires careful balancing of operational requirements with available funding. Ultimately, funding availability depends on the Service's ability to demonstrate the tradeoffs between equipment readiness and maintenance and repair funding based on sound analysis. Analysts at Headquarters, U.S. Marine Corps used optimization to develop multi-year, depot-level maintenance plans that maximize the aggregate value of available equipment while ensuring that an adequate number of each type of asset is available when needed and that annual budget limits are observed. The model we developed, termed the Dynamic Equipment Repair Optimization (DERO), helped achieve a 40% increase ($30M) to program funding for fiscal year 2000 and dramatically reduced the plans' preparation time while producing a balanced mix of equipment to address operational needs.

INTRODUCTION

The 82nd Congress charged the Marine Corps "to be most ready when the Nation generally is least ready" (quoted in Mundy 1993). Even an occasional glance at a newscast confirms this: at all times, 3,600 Marines and sailors are forward deployed aboard amphibious shipping or conducting exercises ashore, with another 3,600 ready to relieve them. The rapid pace and high operational tempo of training and deployments cause valuable, life-saving equipment to fail with increasing frequency and cost, as the Corps' aging ground equipment fleets await modernization and replacement. To complete their demanding missions, forces require a particular minimum quantity of serviceable equipment, but each year, maintenance funding for ground depots falls short of the full amount required to repair or overhaul unserviceable equipment.

In this paper, we develop a methodology to plan and budget for yearly depot-level maintenance requirements of numerous types of ground equipment, while ensuring availability of the minimum required quantity of each type and adhering to annual budgets. First, we describe the context of Marine Corps ground equipment maintenance and describe the major factors associated with it. We explain the incumbent methodology for planning, programming and budgeting for depot-level maintenance and provide motivation for an improved analytical approach. Subsequently we discuss pertinent literature, and explain why we chose an optimization technique for the problem. The final sections illustrate the production of an optimal depot-level maintenance plan for fiscal years 2000–2005, and provide results and observations. An appendix contains a mathematical formulation of DERO and a brief taxonomy of the supporting data.

MARINE CORPS GROUND EQUIPMENT MAINTENANCE

Marine Corps ground equipment maintenance organizations can belong to one of three echelons, in increasing order of capability: organizational maintenance, located at the battalion level; intermediate maintenance, supporting a single Marine Expeditionary Force; and depot or complementary commercial maintenance. The Marine Corps currently owns roughly 350,000 individual pieces of ground equipment that can potentially require repair or rebuild at its maintenance depots (according to Principal End Item Stratification Sheets, Marine Corps Logistics Bases unpublished documents, January 1998). Organizational or intermediate maintenance activities can repair or replace the remainder of the equipment.

Equipment arrives at a depot facility essentially for one of two reasons: either it requires repair beyond the capability of all other echelons of maintenance, or it requires a scheduled rebuild or modification that cannot be performed at the organizational or intermediate echelon. Operators or organizational maintenance personnel first identify equipment requiring repair. If organizational maintenance cannot accomplish the required work, the intermediate maintenance activity supporting the organization examines the equipment. When it is unable to accomplish the repairs, the intermediate activity appeals to the Marine Corps Materiel Command (MATCOM) for performance of depot-level maintenance. MATCOM has two subordinate organizations: Marine Corps Logistics Bases, which administers multi-commodity ground depots in Albany, GA and Barstow, CA and performs many other logistics tasks; and Marine Corps Systems Command (SYSCOM), which performs acquisition-re-

OR METHODOLOGY
Linear Programming
APPLICATION AREA
Military Logistics
Readiness Planning and Programming

lated tasks and provides weapon system and equipment program management for individual systems. These two organizations work together to apply needed modifications and upgrades, and plan equipment fielding and retirement, and determine scheduled overhaul plans for ground equipment to extend its life. The latter function is the second reason equipment arrives at depot facilities—not in response to unscheduled failure, but in accordance with a rebuild or overhaul plan to prevent failures, boost performance, and lower operating and support costs at lower echelons.

Terminology and Scope

We discuss equipment here in terms of *principal end items*, which are fundamentally self-contained pieces of equipment that fulfill a particular mission. For example, the M998 High Mobility Multipurpose Wheeled Vehicle (HMMWV) is an end item, but its engine is not. End items belong to homogeneous classes, referred to by Marines in terms of their five-place alphanumeric *Table of Authorized Materiel Control Number*, abbreviated TAMCN; e.g., the M998 has TAMCN D1158. Marine Corps depots classify the operational state of an end item as either *ready-for-issue* (RFI) or *not ready-for-issue* (NRFI); an asset that is NRFI requires maintenance or repair at the *depot level.* Similarly, an asset that is RFI does not require *depot-level* maintenance, but a unit may consider it unserviceable if it requires organizational or intermediate maintenance in order to function properly. The *Depot-Level Maintenance Program* (DLMP) is the principal agent in the Marine Corps that plans, programs, and budgets for depot-level maintenance of principal end items. This program is prepared on behalf of the Commandant's Deputy Chief of Staff for Installations and Logistics (I&L), in coordination with a number of other agencies. Execution of the principal maintenance and maintenance management tasks falls under the purview of the Commanding General, MATCOM and the Commanding General, Marine Corps Logistics Bases.

Marine Corps Depot Level Maintenance Planning

The principal product of the DLMP is a multi-year plan that lists assets planned for repair or rebuild in each year and the corresponding costs. To develop this plan, the program manager must determine depot maintenance requirements, compete for scarce operations and maintenance funding with other programs, and select a subset of the requirements to fund while still maintaining operational capability in the field. The Marine Corps' Deputy Chief of Staff for Installations and Logistics identifies the specific objectives of the DLMP in accordance with the Defense Planning Guidance (DPG), input from Marine Forces, and guidance from MATCOM and the Marine Corps Combat Development Command (MCCDC). In addition to the broad objective of maintaining the ground equipment fleet for performance of the Service mission, these specific objectives may include, for example, improving combat service support equipment readiness to 90%, or determining how to ramp down maintenance funding for a retiring fleet of assets. The DLMP program manager seeks and obtains funding through the Program Objective Memorandum (POM) process in order to achieve these objectives.

Development of this multi-year plan is a complex process. First, it requires estimates of the number of each TAMCN that will require repair in each quarter. Then, because of limited funding, costs of repairing an end item must be balanced against the need for that item in the fleet—for all end items in the maintenance queue.

Consider first the task of a manager responsible for a single item, such as the Light Armored Vehicle (LAV) depicted in Figure 1. The manager tracks the numbers of assets, serviceable (ready-for-issue or RFI) and unserviceable (not-ready-for-issue or NRFI), owned by Marine Corps organizations, to include sustainment stocks (e.g., war reserve and prepositioned equipment). From historical data, the manager estimates how many assets from each owning organization will require depot maintenance in each fiscal quarter, and improves that estimate by constant coordination with the organizations and at annual maintenance conferences. Once identified, NRFI assets may accumulate awaiting repair, rebuild, or modification for several reasons, mainly facility and technician capacity, parts availability, or funding availability. When the assets depart the maintenance facility, they join a pool of RFI equipment—potentially augmented by newly procured assets—awaiting distribution to own-

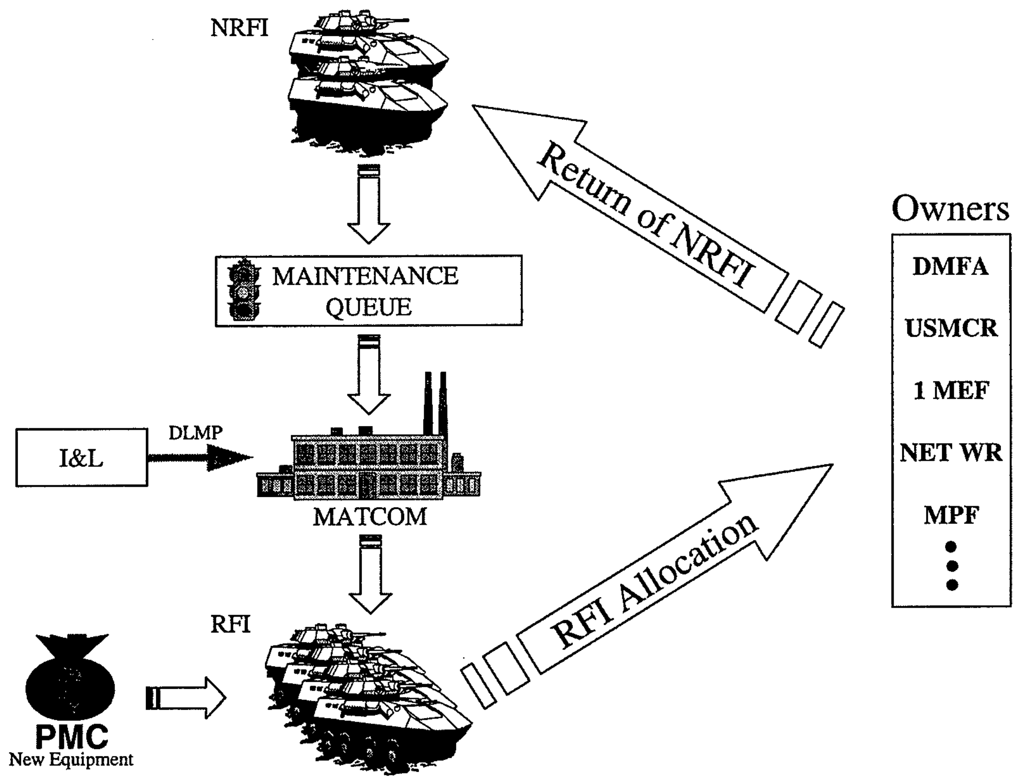

Figure 1. Simplified item manager's view of the Marine Corps' LAV-25 fleet. Unserviceable (NRFI) assets coming from owning organizations enqueue at a depot facility awaiting space, technicians, parts, or funding. Once repairs are complete, assets join a pool of serviceable (RFI) assets, possibly augmented by new assets bought with Procurement, Marine Corps (PMC) funding. The item manager then has to determine where to send the RFI assets. A number of rules apply; generally, the categories or organizations with shortages receive the equipment. The subset of organizations shown in the chart includes the Depot Maintenance Float Allowance (DMFA), a spares pool; the Marine Corps Reserve; I Marine Expeditionary Force; Net War Reserve; and the Maritime Prepositioning Force.

ing organizations. The item manager examines the *asset posture* of each owning organization—the number of RFI assets possessed in relation to the organization's authorized allowance for the item—to help determine where to send RFI assets.

Incumbent Program Management Methodology

The DLMP program manager must consider all end items in the Marine Corps ground inventory potentially requiring depot level maintenance, and with limited funding available, determine which assets to fund in accordance with desired force capabilities. To determine which assets should become DLMP candidates for a given year, the program manager and representatives from MATCOM convene a maintenance conference open to all owning organizations. The conference reviews all pending procurement and redistribution initiatives, rotation and modification plans, and prior estimates of unserviceable returns to the depots. Attendees collate this information and supplement it with Marine Forces' operational needs to develop an unconstrained list of NRFI equipment that, if funded, would not cause the Marine Corps to repair assets in excess of authorized allowances for any item. For example, if the Corps were authorized 100 of a particular radio but owned 130 with 50 NRFI, only 20 would appear on the conference's list. Prior to

1998, the program manager then convened a team of equipment experts who pored over a list of thousands of assets competing for scarce funding. Over a period of weeks, the team attempted to match assets on the unconstrained list of NRFI equipment with corresponding costs, apply some priority to each item, and select a subset of the assets to fund. Invariably, team members selected subsets of NRFI assets that, if funded, would leave owning organizations critically short of other, unfunded items; notably, chronic shortages of engineer equipment and heavy recovery vehicles plagued the program. The management team made ad hoc changes to the lists in an attempt to correct some of these deficiencies, but lacked the ability to make consistent value judgments regarding item-to-item tradeoffs in the face of volumes of quantity, characteristics, and cost data. This technique further precluded the program manager from competing effectively for program funding, because he or she could not show clearly the impacts of increasing or decreasing funding on the resulting availability of equipment.

The Need for Analytical Support

Over 350 different types of items were competing initially for facility space, technicians, and program funding in fiscal year 2000. The program managers sought our help to improve the incumbent methodology for formulating the maintenance plan with the primary objective of providing a balanced mix of equipment Corps-wide to support DPG missions over fiscal years 2000–2005, constrained primarily by limited funding. They wanted us to help determine how to "prioritize" the funding of equipment requiring depot-level maintenance, and to show how increased funding would benefit readiness of these items. Our work was to incorporate results of an ongoing study by the Analytical Systems Engineering Corporation (ASEC 1997), commissioned to review Marine Corps depot-level maintenance processes and to recommend improvements.

RELATED RESEARCH

ASEC's research into Marine Corps depot-level maintenance policies and processes unearthed and documented a wealth of common wisdom and practical concerns within the Marine Corps maintenance and logistics communities, not before collated or published. Their results included a method of developing numeric values to describe the relative operational importance of different types of principal end items; we briefly describe the method, and our use of the resulting values, in the next section.

Other literature addresses the problem of developing and implementing depot-level maintenance policy. The Office of the Secretary of Defense (OSD 1996) provides a comprehensive overview of depot-level maintenance objectives and of the factors affecting Department of Defense (DoD) depot maintenance activities. Kiebler et al. (1996) provide an excellent review of the depot repair cycle, detailing planning and execution processes common to DoD depots.

More specific research has examined impacts of funding on readiness and proposed techniques to select assets for funding and subsequent induction. Scalzo (1998) examines the link between Air Force depot-level maintenance funding and airframe and engine readiness, highlighting the effects of withdrawing war reserve assets to bolster near-term asset availability. Hurry (1996) implements a variety of statistical techniques to investigate how depot-level maintenance affects weapon system availability and the amount of downtime experienced by the systems. O'Malley and Bachman (1990) develop relationships between depot maintenance requirements forecasting, budgeting, and aircraft readiness for the Air Force and provide managerial recommendations to improve the planning and budgeting process. One class of models, developed and tested in the Air Force and Army, uses an algorithm referred to as "marginal analysis" to prioritize spares procurement (Slay et al. 1996) or near-term depot maintenance execution and asset distribution (Abell et al. 1992) in order to maximize specific measures of aggregate availability.

Two studies address distinct aspects of the problem of developing a depot-level maintenance plan for Marine Corps ground equipment in an environment of constrained funding. Foulk (1985) documents difficulties in separating Marine Corps Reserve funding from that used to pay for active force or sustainment asset overhaul or repair, a chronic problem continuing today. Bargeron (1995) uses integer programming to develop optimal tank-specific

maintenance schedules while maximizing tank readiness under a number of policies.

SELECTING AN APPROACH

Many of the aspects of previous research had potential applicability to parts of our problem. Initially, we developed rudimentary principal end item reliability measures (I&L unpublished paper, 1997) based on Marine Corps data and attempted to integrate them into a simulation model of the depot repair process utilizing priority queues (see, e.g., Wolff 1989). The resulting model was disappointing: it was not easily explained intuitively from the perspective of the program manager, and it was relatively time-consuming to modify and run. Further, we learned during its development that the program managers required specific recommendations regarding which assets to fund and the anticipated readiness consequences, and that the Headquarters level would initially be very satisfied without a stochastic representation of asset failure. In fact, our probabilistic treatment of the problem produced some confusion because the role of the maintenance conferences was largely to determine the next year's workload as closely as possible, and all concerned felt that deviation from the turn-in quantities developed at the conference should be avoided. The program managers indicated that sensitivity to annual budget decisions was of paramount interest. Following these discussions we sought to develop a prescriptive model, simple, robust and reflective of Marine Corps-specific concerns, to support development of relatively long-range multi-commodity depot level maintenance plans. We required enough detail to link specific maintenance funding decisions for individual TAMCNs to accepted readiness measures of both that TAMCN and the entire ground equipment fleet. Ultimately, the long decision horizon (two to six years), large numbers of assets involved, emphasis on maximizing equipment readiness, and other factors led us to evaluate an optimization approach. We intended only to provide a rough prototype to build the program managers' confidence and to demonstrate that even a simple model could capture the essential elements of the problem if the model were properly designed. Early results were so encouraging, however, that the program managers urged us to refine the prototype for immediate use.

THE DYNAMIC EQUIPMENT REPAIR OPTIMIZATION (DERO) MODEL

After several iterations discussing relevant assumptions and implementing refinements to the prototype linear program with the program managers and MATCOM personnel, we were able to provide a concise verbal statement of our objective and the factors constraining our decisions that met with approval. The model should maximize the readiness of depot-level reparable ground equipment to both operating forces and sustainment stores (e.g., war reserve) across all years in the decision horizon, adhering to annual budgets and to minimum readiness percentages for each TAMCN in each year. To accomplish this, it should decide only how many of each TAMCN can be funded in each year; all other information must be provided. In most cases, equipment not funded in one year should be carried over to the next, so that funding decisions in one year impact the equipment readiness and funding decisions in subsequent years. In conjunction with the program managers, we agreed that constraints on facility space and technicians were not of primary concern, because more than one depot were available and additional work could be performed at commercial facilities if required. Further, we agreed on the assumption that if an asset were funded for depot maintenance in a particular year, it would complete the maintenance cycle and would be available at the end of that year. Finally, if minimum readiness percentages were not attainable because of limited funding, the model should develop a workable solution anyway. We provide a mathematical formulation of this model in the appendix, where we describe the objective function and constraints explicitly.

Defining Readiness and Developing the Objective Function

In conjunction with the War Reserve and Readiness Appraisal Section at Headquarters, U.S. Marine Corps (HQMC), we defined the readiness of a TAMCN as its "E-rating,"

$$E = \min\left\{\frac{\text{number of assets RFI}}{WMR}, 1\right\},$$

where WMR represents the *war materiel requirement*—the total number of assets authorized to

all Marine Corps organizations and in sustainment stocks, also known as the *approved acquisition objective.* This measure does not represent equipment readiness at the unit level, because an RFI asset could be awaiting work at an organizational or intermediate maintenance activity. This issue is beyond the scope of depot-level maintenance planning, because organizational and intermediate maintenance are funded and managed by Marine Forces commanders with their own operations and maintenance accounts.

With a readiness measure in hand, we sought to use it to drive the model's funding decisions. One principal objective of DERO was to incorporate judgments about the warfighting value of individual TAMCNs, and to use those judgments quantitatively to make tradeoffs between different types of equipment competing for funding in the maintenance plan. ASEC's value model integrates judgments regarding the relative importance of each TAMCN in each of four specific operational scenarios with practical concerns about prioritizing critical weapons systems routinely highlighted in readiness reports and retrieving and funding assets planned for modification or overhaul (instead of routine repair). This value model assigns the same numeric score to all assets with the same TAMCN, and indicates the importance of one TAMCN relative to the others in the context of the DLMP. We used these scores as linear additive weights on asset E-ratings for each TAMCN in each year to form our piecewise-linear objective function (representative of an overall readiness figure). We discounted out-year decisions in the objective function, because POM decisionmakers typically focus only on one or two consecutive years. In each year, we penalized the cases in which E-ratings fell below the specified minimum percentages.

To keep track of RFI and NRFI equipment quantities from year to year, we employ the basic flow-balance structure shown in Figure 2. The quantity of RFI equipment increases from one year to the next with the addition of newly issued assets or NRFI assets receiving depot maintenance funding. It decreases by the esti-

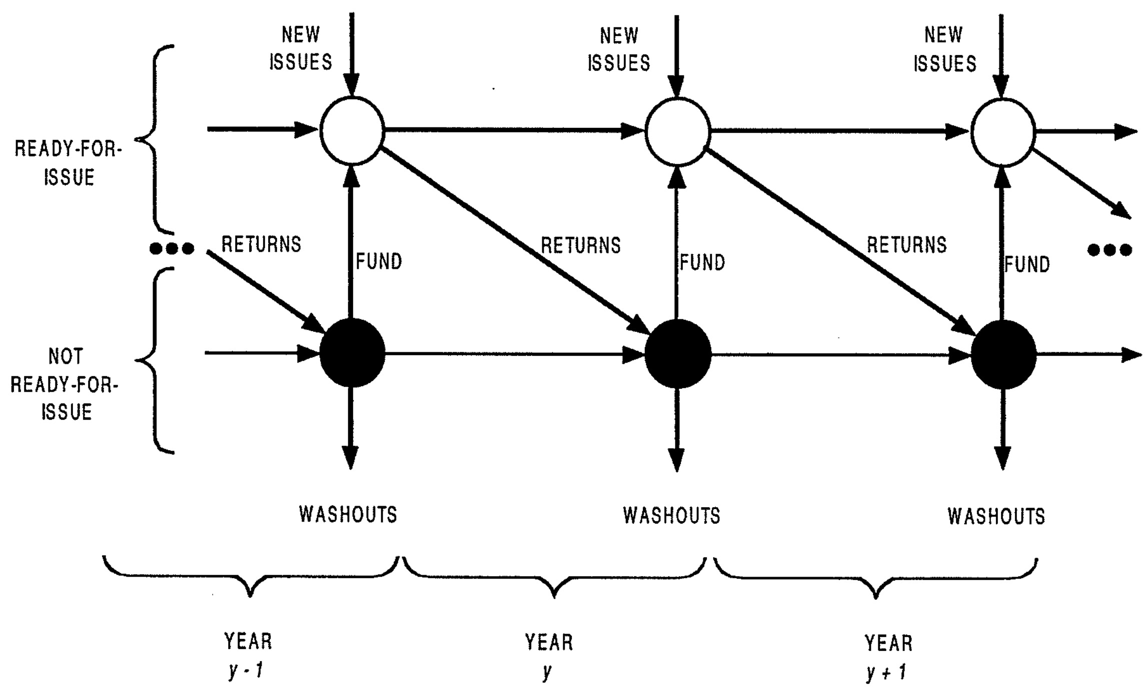

Figure 2. Model treatment of RFI and NRFI equipment for each TAMCN (equipment type). Quantities of equipment newly issued and returned as unserviceable are data inputs; vertical arcs labeled FUND correspond to decision variables and carry a per-unit cost corresponding to repair cost estimates.

mated number of failures. At the end of each year, we compare the number of RFI assets against the WMR for each TAMCN to determine that TAMCN's individual E-rating and its contribution to overall equipment readiness.

DERO Implementation in POM 00 (2000–2005)

The Marine Corps' POM describes, by appropriation, the way the Marine Corps plans to spend its money over a six-year period, with emphasis on the first and second years. The DLMP portion of the POM contains an itemized breakdown of assets to be funded by commodity (ordnance, communications, etc) in terms of quantity and cost. Obtaining Service approval of the DLMP POM submission requires a detailed breakdown by TAMCN and a clear link of allocated funding to improved equipment readiness, particularly in the first of the six years. As a starting point for deliberations, the Department of the Navy allocates the Marine Corps its own Total Obligation Authority, representing the total funding available to the Marine Corps each year. The Marine Corps subdivides this total among all its programs competing for funding to form program "baselines." When these baseline figures and preparation guidance were distributed to the program managers, our work began in earnest. DLMP program management wanted us to design a sequence of model runs to investigate the readiness impact of increases to fiscal year 2000 program funding from the baseline up to the total cost of all unserviceable returns occurring in that year (Figure 3). Corresponding to each funding level examined, we were to show what equipment we would pay for and how readiness improved for each by the end of the fiscal year. The Service POM coordinators further wanted us to show a point of diminishing returns to overall equipment readiness as funding increased.

Figure 4 shows the individual TAMCNs improving as we added funding to fiscal year (FY) 2000 above the program baseline; Figure 5 shows the decreasing marginal returns to readiness as program funding increases.

Average readiness for all TAMCNs considered increased by only just under 1%, but this is primarily due to the large number of assets evaluated and the extremely costly nature of the work. For example, the M88 tracked recovery vehicle, fully funded at the $73M baseline,

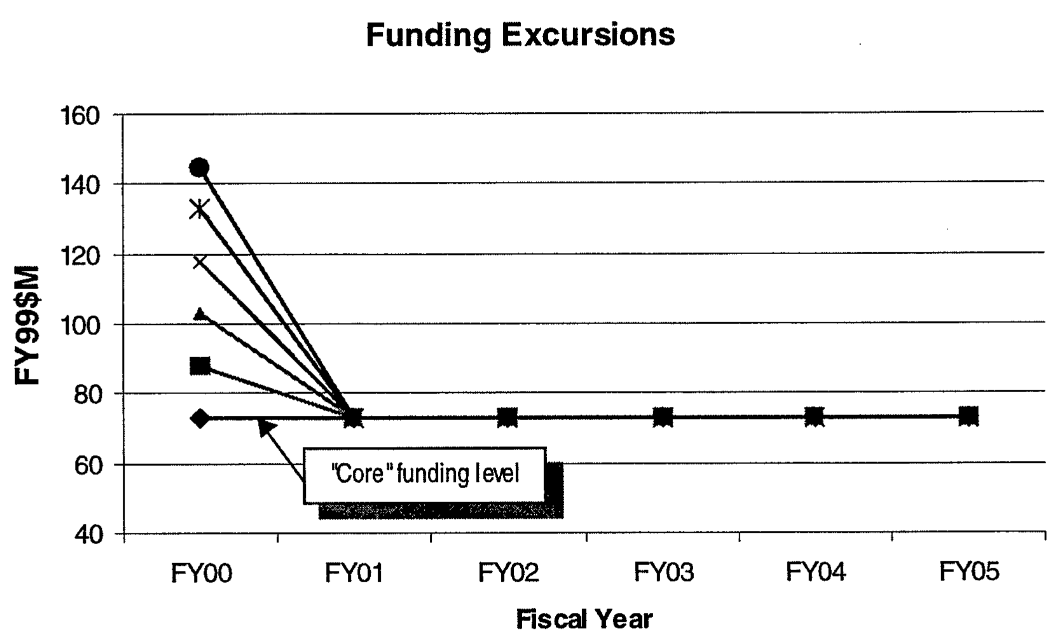

Figure 3. Alternative funding scenarios examined for POM-00. The baseline case corresponded to spending $73M in constant dollars each year; each alternative scenario increased program funding in FY00 in $15M increments and left funding in later years at the established "core" level of $73M.

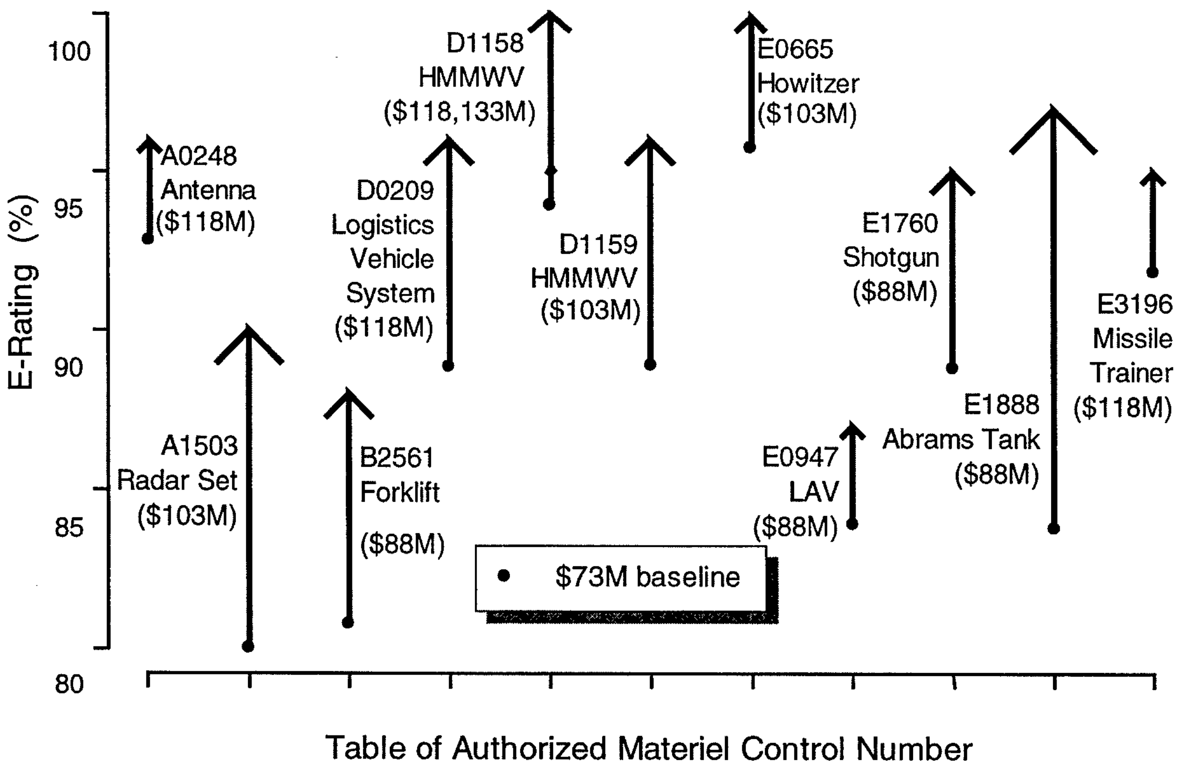

Figure 4. Readiness E-rating improvements resulting from funding alternatives depicted in Figure 3. Asset fleets (TAMCNs) improving above the baseline are shown by the arrows; those not shown (in excess of 100 TAMCNs) do not receive additional funding from the model beyond that allocated from the baseline budget. The base of the arrow indicates the readiness rating of the equipment when the program receives the baseline funding level. The tip of each arrow indicates the readiness achieved by DERO at the end of FY00 when program funding is increased to the amount shown in parentheses below the equipment nomenclature.

is a critical asset that enables recovery of disabled tanks and other heavy equipment on the battlefield or during an exercise. No other asset can perform the M88's duties except perhaps another main battle tank, and the M88 was designed for the lighter M60 tank—making its breakdowns more frequent with the heavier Abrams of today. Item managers at MATCOM estimated that 13 such vehicles would fail and require repair or overhaul in FY 2000; these estimates were confirmed by owning organizations. According to MATCOM, typical repairs on failed M88s cost $432,000 per asset at the depot level. If none of the 13 were funded, M88 readiness would plummet to 77%, 8% below the desired 85% minimum for this TAMCN. Funding all 13 at $5.6M bolstered this figure to 95%; but this change only increased average readiness by 0.16% (all other funding decisions held constant). Further examples of critical equipment appearing in Figure 4, particularly the readiness improvements of 10% for M-1A1 Abrams tanks and 7% for the Logistics Vehicle System tractor, provide some perspective on the small average readiness improvement overall.

OBSERVATIONS AND CONCLUSIONS

The detail visible in Figures 4 and 5 was exactly what decisionmakers wanted the program manager to present. With the diminishing returns shown in Figure 5, and TAMCN-level detail shown in Figure 4 and in model output, we successfully justified expenditures of $118M for FY00. The unusual scale of Figure 5—showing an increase of only 0.7% in average E-rating for the recommended increase in investment—required the substantive detail of Figure 4 to

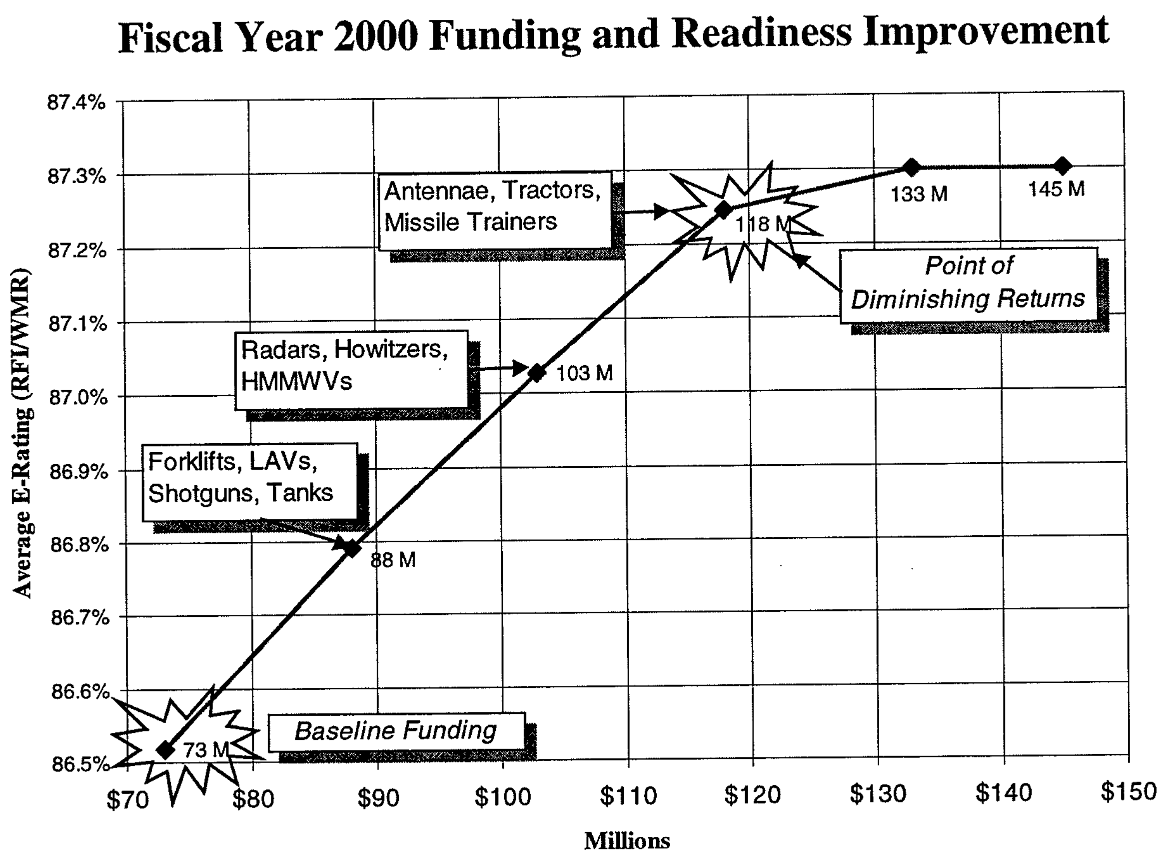

Figure 5. Relationship of FY00 funding to improvement in equipment readiness (E-rating). Increases in increments of $15M above the baseline of $73M cause additional assets to be added to the plan. Some quantities of these TAMCNs had already been funded at $73M to ensure the minimum desired readiness levels specified for each were met. Readiness improvement per dollar spent began to decline as money was committed to the program above $118M. This occurs below 100% because the program manager withheld a number of assets from consideration for repair for administrative reasons. The E-rating scale is discussed further in the text.

explain. We provided the explanation in the previous section's discussion of Figure 4 and showed the TAMCN-level detail, in particular pointing out the drastic improvement in tank readiness; this proved to be a convincing argument.

The first-year equipment mix was the subject of more scrutiny than any other year, and participants were pleased to see a balanced mix of equipment emerge that appeared to them to satisfy operational needs. Though the Marine Corps later reduced the funding commitment to $102M because of late-breaking developments in SYSCOM procurement plans, program funding increased roughly $30M, or 40%, above the program baseline.

Development of a centralized depot-level maintenance plan is an ideal opportunity for application of OR techniques. The variety and quantity of data are difficult to manage manually; initial POM analyses performed with the model involved 118 distinct TAMCNs, and the maintenance conference forecasted in excess of 13,000 assets to be added annually to previous backlogs of equipment. SYSCOM provided relatively firm data regarding replacement plans for several types of engineering and motor transport equipment, requiring an assessment of the resulting impact on maintenance funding for remaining assets. The various POM committees took an intense interest in this impact; to the dismay of maintenance experts and operating forces, the committees' initial inclination was to remove funding abruptly from older assets being gradually replaced. The alarm over this issue extended to the program

managers, because they had not previously been able to determine how to phase out maintenance funding for retiring assets over time while remaining relatively certain of retaining the assets' capability.

Implementation of an optimization model in this context proved to be extremely beneficial. Foremost, all concerned parties had the opportunity to work with each other and with ASEC in the development of the system for calculating equipment scores. Subsequent use of those scores in an optimization ensured expert judgment could be applied consistently across multiple assets in multiple years toward the same goal of maximizing readiness. Consistency and optimality remained possible even with the confusing introduction of long-term fielding and retirement plans into the analysis and with the further difficulties of repeated "what-if" budget drills.

Ongoing and Future Work

These positive factors helped us to promote our model effectively and to increase the program managers' confidence in optimization, an unfamiliar, relatively sophisticated technique. Several difficulties remain. Foremost, planned rebuilds or modifications sometimes require "all-or-nothing" asset recovery over a particular time period, so that carcasses are available for application of modification kits or so that shop floor or contractual requirements can be met over a limited period of time. Our model currently requires these situations to be "preprocessed;" we are currently working to overcome this deficiency.

Two clear opportunities exist for related future work: implementing a decision support system similar to RAND's (Abell et al. 1992) for short-term planning and prioritization at the depots; and integrating procurement and maintenance decisions.

- **Short-term planning tools.** As DERO considers high-level funding decisions on a yearly basis, the logistics bases require a more frequent assessment and prioritization tool to help execute the plans. Capacity and workforce constraints are among a host of daily problems that require schedule alterations. A tool to use detailed, real-time facility data to help manage multi-commodity maintenance would be very beneficial.
- **Integration of procurement decisions.** DERO treats procurement of new assets, development of fielding plans for them, and scheduling of rebuilds or modifications as part of the "state of nature." In fact, determination to purchase modification kits, for example, requires that funding be available to apply them at a depot. Also, increasing failures requiring depot-level maintenance should indicate the need for modernization, and these factors should be weighed on the basis of cost and readiness in determining when modernization should occur (see, e.g., Brown et al. 1991). When we developed this model, management practices did not allow this coordination to take place; the problem persists today. With the recent advent of MATCOM to coordinate acquisition and life cycle management activities in the Marine Corps, analysts have a new opportunity to help shape a new generation of ground equipment in more affordable ways.

APPENDIX 1: LIST OF ACRONYMS

ASEC	Analytical Systems Engineering Corporation
DERO	Dynamic Equipment Repair Optimization
DLMP	Depot Level Maintenance Program
DoD	Department of Defense
DPG	Defense Planning Guidance
FY	Fiscal Year
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HQMC	Headquarters, U.S. Marine Corps
I&L	Installations and Logistics
LAV	Light Armored Vehicle
MATCOM	Materiel Command
MCCDC	Marine Corps Combat Development Command
NRFI	Not Ready-For-Issue
OSD	Office of the Secretary of Defense
POM	Program Objective Memorandum
RFI	Ready-For-Issue
SYSCOM	Systems Command
TAMCN	Table of Authorized Materiel Control Number

WMR War Materiel Requirement

APPENDIX 2: MODEL FORMULATION

Indices

t Table of Authorized Materiel Control Number (type of equipment),

y Fiscal years, y = 1, 2, . . . ;

Data

α Discount factor used to emphasize near term decisions ($\alpha \leq 1$),

$budget_y$ Depot repair budget for principal end items in year y (constant dollars),

$cost_t$ Cost to repair one asset of TAMCN t,

$issue_{t,y}$ Number of TAMCN t assets newly issued in year y,

pen_t Penalty cost assessed for each TAMCN t asset short of availability goal, each year,

$rtgt_{t,y}$ Target availability percentage of TAMCN t assets in year y,

sbl_t Starting backlog of unserviceable TAMCN t assets (year 0),

$srfi_t$ Starting number of serviceable TAMCN t assets (year 0),

$usr_{t,y}$ Planned number of unserviceable returns of TAMCN t assets in year y,

$value_t$ Relative warfighting value of TAMCN t assets, and

$wmr_{t,y}$ War Materiel Requirement for TAMCN t assets in year y;

Variables

$NRFI_{t,y}$ Number of TAMCN t assets not ready-for-issue (unserviceable) at beginning of year y,

$RFI_{t,y}$ Number of TAMCN t assets ready-for-issue (serviceable) at beginning of year y,

$RPR_{t,y}$ Number of TAMCN t assets funded for repair or overhaul in year y,

$SCORE_{t,y}$ Total warfighting value of all TAMCN t assets at end of year y; and

$SHORT_{t,y}$ Shortfall of TAMCN t ready-for-issue assets at end of year y.

Formulation:

Maximize

$$\sum_t \sum_y \alpha^{y-1}(SCORE_{t,y} - pen_t SHORT_{t,y}) \tag{1}$$

Subject to

$$\sum_t cost_t RPR_{t,y} \leq budget_y \quad \forall y; \tag{2}$$

$$SCORE_{t,y} \leq \frac{value_t}{wmr_{t,y}} RFI_{t,y} \quad \forall t, y; \tag{3}$$

$$NRFI_{t,y} = sbl_t + usr_{t,y} - RPR_{t,y} \quad \forall t, y = 1,$$
$$NRFI_{t,y} = NRFI_{t,y-1} + usr_{t,y} - RPR_{t,y} \quad \forall t, y > 1; \tag{4}$$

$$RFI_{t,y} = srfi_t + RPR_{t,y} - usr_{t,y} + issue_{t,y} \quad \forall t, y = 1, RFI_{t,y} =$$
$$RFI_{t,y-1} + RPR_{t,y} - usr_{t,y} + issue_{t,y} \quad \forall t, y > 1; \tag{5}$$

$$RFI_{t,y} \geq rtgt_{t,y} wmr_{t,y} - SHORT_{t,y} \quad \forall t, y; \tag{6}$$

$$SCORE_{t,y} \leq value_t \quad \forall t, y; \tag{7}$$

all variables ≥ 0; *RFI, NRFI, RPR* integer.

Data Description and Explanation

The central point of contact for all data implemented in this model is the Maintenance Policy Section, Logistics Plans, Policy, and Strategic Mobility Division, Installations and Logistics Department, Headquarters, U.S. Marine Corps. The POM Working Group provided pre-

liminary annual budgets and guidance regarding how to vary them for sensitivity analysis. Repair costs, initial asset postures, unserviceable returns forecasts, and war materiel requirements data were provided by the Life Cycle Management Center, Marine Corps Logistics Bases, Albany, Georgia. Penalty costs were developed by the author as shown in Figure 6. Minimum readiness targets were set at a default of 70%, except for TAMCNs and years in which the Marine Corps owned less than 70% of the WMR; we lowered targets to the maximum achievable percentage in those cases. In other cases, we made upward adjustments to the targets to reflect problematic scenarios or specific requirements we could confirm.

The Objective Function

The objective function is a weighted sum of TAMCN E-ratings. The term corresponding to a single TAMCN in a single year appears in Figure 6. As the fraction of assets within that TAMCN increases from the minimum desired percentage to 100% of the WMR, the objective function contribution increases linearly to achieve a maximum of $value_t$ (appearing as w in the figure). A TAMCN could achieve more than 100% of the WMR RFI if the Marine Corps possessed excess equipment. We placed upper bounds on the *SCORE* variables in order not to provide incentive to repair equipment in excess of authorized quantities. We set the penalty costs so that a TAMCN's objective function contribution would be negative if too few assets were funded to achieve the minimum desired quantity of RFI equipment.

Constraints

Constraints [2] limit repair expenditures to the budget in each year. Constraints [3] limit each TAMCN's objective function contribution in a given year to its end-of-year readiness weighted by its assessed value. Constraints [4] and [5] are "bookkeeping" relationships to track numbers of RFI and NRFI assets correctly from year to year based on fielding data and funding decisions (Figure 2). Constraints [6] require the number of assets RFI for each TAMCN in each year to exceed a target percentage of the WMR, and allow violation at linear cost. Inequalities [7] remove incentive for the model to repair excess equipment; they are implemented as upper bounds on variables instead of as part of the constraint set.

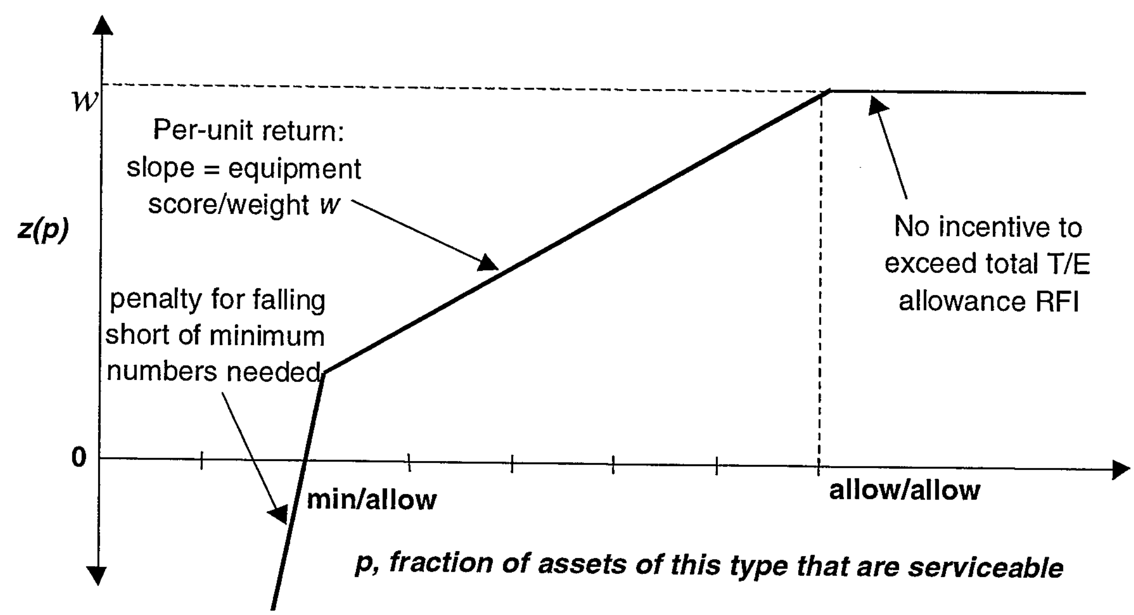

Figure 6. Objective function contribution of a single TAMCN in a single year.

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Information is a strategic resource that is vital to national security and well being. Joint Doctrine 3-13 defines Information Operations (IO) as actions taken to affect an adversary's information and information systems while defending one's own information and information systems. This definition covers not only crisis or conflict driven information warfare, but also a wider set of objectives and goals on a continual, on going, basis. These goals include offensive, defensive, and assurance considerations for information, information systems, and information processes. The recent Presidential Commission on Critical Infrastructure Protection highlights how these issues affect not only the military, but also industry, government, and citizens in general.

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UNMANNED AERIAL VEHICLE (UAV) ROUTE SELECTION USING REACTIVE TABU SEARCH

by Joel L. Ryan, T. Glenn Bailey, James T. Moore, and William B. Carlton

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AN HISTORICAL PERSPECTIVE ON OPERATIONS RESEARCH IN THE UNITED STATES AIR FORCE

edited by Dr. Carl M. Harris, and Col. Frank T. Trippi (USAF, ret.)

Carl Harris is the coauthor of three editions of the textbook *Fundamentals of Queueing Theory*, co-editor of *The Encyclopedia of Operations Research and Management Science*, and the author or coauthor of approximately 80 previous papers in the open professional literature. He was President of the Operations Research Society of America in 1990–91 and continues to be active in a variety of societal activities for INFORMS, including a current tour on its History and Tradition Committee. His current research interests include applied probability and statistics, queuing theory, simulation, and public systems analysis.

Frank Trippi is currently the Chair of the Public Awareness Committee of INFORMS, which has created educational outreach materials—videos, teacher instructional modules, and teachers' workshops—for the middle, high school and community college levels over the past 11 years. He is currently also a member of the INFORMS History and Tradition Committee. A retired Air Force Reserve officer, his prior military and civilian experiences were exclusively in the intelligence field, ending in an assignment as the Assistant Director, Systems Analysis Division, Naval Facilities Engineering Command. Both Col. Trippi and co-editor Carl Harris share the distinction of originally hailing from Brooklyn, New York.

MODELLING THE MOBILE LAND BATTLE: COMBAT DEGRADATION AND CRITERIA FOR DEFEAT

by L. R. Speight and D. Rowland

Ron Speight is currently a freelance consultant in the field of military operations research. His first degree was in psychology, and for a number of years he worked as a human factors expert for the British Army. In mid-career he obtained a doctorate in Operations Research, and then switched to that discipline. Having concluded a number of OR studies he was promoted to a succession of scientific administrative posts in the UK Ministry of

Defence. In early 1985 he was appointed Chief of the Operations Research Division at the SHAPE Technical Centre in the Hague, holding that position until his retirement in 1992. He has remained active in the fields in which he developed a professional interest, and likes to undertake private research on some of the more fundamental problems of battle modelling. At the same time he tries to ensure that this activity is not at the expense of travelling the world, and that it does not exclude other interests.

David Rowland started his professional career in defence by modelling off road mobility at the UK Military Vehicles Engineering Establishment. Passing on to what is now the Centre for Defence Analysis (High Level Studies), he then had a long association with tactical field trials, producing a string of analyses and reports pertaining to infantry and armoured warfare. From 1992 until his recent retirement he was the leading light of the Historical Analysis Group at the Centre. Now that he is officially retired he is, inevitably, busier than ever undertaking military historical analyses. Nevertheless, with difficulty his wife does persuade him from time to time to take time off, and to visit their favourite retreats in the Welsh mountains.

ENVIRONMENTAL FACTORS IN AMPHIBIOUS OPERATIONS

by Donald R. Del Balzo, Paul A. Vodola and Jerry D. Beveridge

Mr. Del Balzo received BS ('70) and MS ('71) degrees in Physics from Virginia Polytechnic University. Since then he has worked as an experimental physicist for the Naval Research Lab in the areas of underwater environmental acoustics, magnetics, and signal processing, with application to ASW and MCM. His work covers many active and passive sonar applications involving basic and applied research as well as transitions to Fleet demonstrations. His latest efforts involve operations analysis to optimize ASW search tactics in littoral environments using genetic algorithms.

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Mr. Jerry D. Beveridge has been employed by Systems Planning and Analysis, Inc. since September 1987. He is a Program Manager and Senior Surface Warfare Analyst. Prior to joining SPA, Mr. Beveridge had completed a distinguished twenty-seven year career with the U.S. Navy. He served on board destroyers, cruisers, aircraft carriers, and amphibious and logistics force ships. He also served ashore on the staffs of the Chief of Naval Operations, the Commander, Naval Air Forces, Pacific Fleet, and Chief of Naval Research. In 1970 he received a Masters of Science degree in Operations Research from the Naval Postgraduate School.

DEPOT-LEVEL MAINTENANCE PLANNING FOR MARINE CORPS GROUND EQUIPMENT

by Christopher A. Goodhart

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All submissions must include a statement of the major contribution. For applications articles, authors are requested to submit a **letter** to the editor—exerpts to be published with the paper—from a **senior decision-maker** (government or industry) stating the benefits received from the analysis described in the paper.

To facilitate the review process, authors are requested to categorize their articles by **application area** and **OR method**, as described in Table 1. Additional categories may be added. (We use the MORS working groups as our applications areas and our list of methodologies are those typically taught in most OR graduate programs.)

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TABLE 1: APPLICATION AREAS & OR METHODS

Composite Group	APPLICATION AREA	OR METHODOLOGY
I. STRATEGIC & DEFENSE	Strategic Operations Nuclear Biological Chemical Defense Arms Control & Proliferation Air & Missile Defense	**Deterministic Operations Research** Dynamic Programming Inventory Linear Programming Multiobjective Optimization Network Methods Nonlinear Programming
II. SPACE/C41SR	Operational Contribution of Space Systems C41SR Operations Research & Intelligence Information Warfare Electronic Warfare & Countermeasures Unmanned Systems Military Environmental Factors	
III. JOINT WARFARE	Land & Expeditionary Warfare Littoral Warfare/Regional Sea Control Power Projection, Planning, & Execution Air Combat Analysis & Combat ID Special Ops/Operations other than War Joint Campaign Analysis	**Probabilistic Operations Research** Decision Analysis Markov Processes Reliability Simulation Stochastic Processes Queuing Theory
IV. RESOURCES	Mobility & Transport of Forces Logistics, Reliability, & Maintainability Manpower & Personnel	
V. READINESS & TRAINING	Readiness Analytical Support to Training & Mission Rehearsal Battlefield Performance, Casualty Sustainment, & Medical Planning	**Applied Statistics** Categorical Data Analysis Forecasting/Time Series Multivariate Analysis Neural Networks Nonparametric Statistics Pattern Recognition Response Surface Methodology
VI. ACQUISITION	Measures of Effectiveness Test & Evaluation Analysis of Alternatives Cost Analysis Decision Analysis	
VI. ADVANCES IN MILITARY OR	Modeling, Simulation, & Gaming Revolution in Military Affairs (Long Range/Strategic Planning) Computing Advances in Military OR	**Others** Advanced Computing Advanced Distributed Systems (DIS) Cost Analysis Wargaming

Length of Papers

Submissions will normally range from 10–30 pages (double spaced, 12 pitch, including illustrations). Exceptions will be made for applications articles submitted with a senior decision-maker letter signed by the Secretary of Defense.

Format

The following format will be used for dividing the paper into sections and subsections:

TITLE OF SECTIONS

The major sections of the paper will be capitalized and be in bold type.

Title of Subsections

If required major sections may be divided into subsections. Each subsection title will be bold type and be Title Case.

Title Subsection of a Subsection

If required subsections sections may be divided into subsections. Each subsection title will be Title Case. Bold type will not be used.

Paper Electronic Submission with Figures, Graphs and Charts

After the article is accepted for publication, an electronic version of the manuscript must be submitted in Microsoft Word or WordPerfect. For each figure, graph, and chart, please include a camera-ready copy on a separate page. The figures, graphs, and tables should be of sufficient size for the reproduced letters and numbers to be legible. Each illustration must have a caption and a number.

Mathematical and Symbolic Expressions

Authors should put mathematical and symbolic expressions in Microsoft Word or WordPerfect equations. Lengthy expressions should be avoided.

Footnotes

We do not use footnotes. Parenthetical material may be incorporated into a notes section at the end of the text, before the acknowledgment and references sections. Notes are designated by a superscript letter at the end of the sentence.

Acknowledgments

If used, this section will appear before the references.

References

References should appear at the end of the paper. The references should be unnumbered and listed in alphabetical order by the name of the first author. Please use the following format:

For journal references, give the author, year of publication, title, journal name, volume, number, and pages—for example:

Harvey, R.G., Bauer, K.W., and Litko, J.R. 1996. Constrained System Optimization and Capability Based Analysis, Military Operations Research, Vol 2, No 4, 5–19.

For book references, give the author, year of publication, title, publisher, and pages—for example:

Morse, P.M., and G.E. Kimball. 1951. Methods of Operations Research. John Wiley, 44–65.

For references to working papers or dissertations cite the author, title, type of document, department, university, and location, for example:

Rosenwein, M. 1986. Design and Application of Solution Methodologies to Optimize Problems in Transportation Logistics. Ph.D. Dissertation. Department of Decision Sciences, University of Pennsylvania, Philadelphia.

Appendixes

If used, this section will appear after the reference.

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